A Leachate Recycle Management and Pollutant Loading Strategy at Codisposal Landfill Sites

A Special Research Problem

Presented to

The Faculty of the School of Civil Engineering
Georgia Institute of Technology

by

Stephen F. Tyahla

In Partial Fulfillment
of the Requirements for the Degree of
Master of Science in Environmental Engineering

July 1989

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF CIVIL ENGINEERING
ATLANTA, GEORGIA 30332

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Abstract

During an experimental period of over three years, ten pilot-scale simulated landfill columns were operated to investigate the fate of selected inorganic and organic priority pollutants codisposed with shredded municipal refuse, and their effects on the natural stabilization of the refuse. The columns were operated in five similarly loaded pairs employing either single pass leaching, or leachate containment, collection and recirculation. One pair received only shredded municipal refuse and served as controls while the remaining four pairs received refuse, equal quantities of organic priority pollutants, and varying loadings of inorganic priority pollutants in the form of heavy metal sludges. Measurements of gas production and analyses of the gas and leachate produced were used to determine the relative effects of the pollutant loadings, under the two leachate management strategies, on the microbially-mediated stabilization processes.

The results provided additional evidence of the accelerating effect of leachate recycle on landfill stabilization, and some indication of the enhancing influence that leachate recycle had on the inherent assimilative capacity of domestic refuse for the loaded pollutants.

Based upon the results, inferences regarding leachate management and metal sludge loadings are made. With regards to the metal loadings, both the gross loading as well as the manner of application are discussed. Avoidance of acid shock during the transition to the methane production phase of landfill stabilization was a primary hurdle, while loading chemical contaminants in discrete layers in codisposal operations utilizing leachate recycle appeared to offer the greatest advantages. However, further research is recommended which more directly investigates the effects of varying degrees of mixing when codisposing such pollutants with landfilled refuse.

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Chapter I: Introduction

It has been projected that in 1990, between 295 and 341 million metric tons of solid waste will be generated in the United States (Doggett et al., 1980). Ultimate disposal of the vast majority of this waste will likely be accomplished through the continuing practice of sanitary landfilling.

Today's engineered, sanitary landfill is a well-planned facility that makes efficient use of a land area for the economical and environmentally sound disposal of solid waste. Three salient design/operational features of the sanitary landfill account for its effectiveness: controlled disposal, leachate management, and gas management. Management with daily and final soil covers over the compacted layers of refuse, provides vector and odor control, as well as an additional source of microbial seed for biodegradation of organic matter within the fill. The use of natural and/or synthetic liners provides containment for any liquid percolating through the compacted waste and soil layers, while drainage systems installed above the liner collect and transport this liquid (called leachate) for treatment and ultimate disposal. The gas evolved through biodegradation, primarily carbon dioxide and methane, can be either vented to the atmosphere, flared, or

recovered for its energy value. In 1983, it was estimated that approximately 26.7 million metric tons of hazardous waste were placed in sanitary landfills; this amount is projected to be reduced to about 10 million metric tons in 1990 (Naber, 1986).

While receiving primarily municipal solid wastes or refuse, sanitary landfills may also serve as ultimate disposal sites for quantities of hazardous chemical wastes. Current U.S. Environmental Protection Agency (EPA) regulations exempt all household waste from hazardous waste regulations, as well as hazardous wastes produced by industries which are "conditionally exempt small quantity generators" (U.S. EPA, 1987). Thus, it is currently legal for households, and industries generating no more than 100 kilograms of hazardous waste per month, to select sanitary landfills for solid waste disposal.

Codisposal of hazardous wastes with municipal and industrial refuse in landfills may lead to the contamination of ground and surface waters if leachate containing hazardous constituents is permitted to migrate outside the containment system. While sanitary landfill leachate alone may contain sufficient quantities of organic matter to impair the quality of surface and subsurface waters, the addition of hazardous materials poses an

additional threat, usually manifested in the form of toxicity. Moreover, the presence of certain inorganic chemical compounds, such as heavy metals, may also inhibit the microbially-mediated biodegradation processes within the landfill, resulting in a delay of the progress of stabilization of the refuse constituents, and prolonged periods of potential leachate migration.

As mentioned above, the modern sanitary landfill alleviates many of the threats associated with uncontrolled leachate migration through the use of leachate containment, collection and treatment. Leachate is typically collected and then treated using a variety of biological, physical and chemical unit processes. Within the last ten years, however, the containment, collection and recirculation by re-application of leachate to the refuse has proven beneficial in providing significant *in situ* treatment of the leachate, while greatly accelerating the natural stabilization processes within the solid waste matrix.

To provide additional evidence of the efficacy of such a landfill management option, the present study was conducted to evaluate the behavior and fate of selected inorganic and organic priority pollutants codisposed with municipal solid waste in simulated landfills. Operationally, both single pass leaching and leachate collection and recirculation were examined with ten lysimeter columns. Analyses of the

leachate produced and the gases evolved were used to evaluate the hazardous constituent assimilative capacity and attenuation mechanisms present in the simulated landfill columns, and to observe the impact that the codisposed hazardous contaminant loadings had on the natural processes of landfill stabilization. In addition, a proposed leachate management and pollutant loading scheme for codisposal landfill operations using leachate recycle was developed.

Chapter II: Review of the Literature

Sanitary Landfill Stabilization

Solid wastes contained within a sanitary landfill undergo a variety of simultaneous physical, chemical and biological transformations. Generally, as described by Tchobanoglous, et al., (1977), these changes include: (1) the biological decay of putrescible material (either aerobically or anaerobically) with the evolution of gases and liquids; (2) chemical oxidation of materials; (3) escape of gases from the landfill and lateral diffusion of gases; (4) movement of liquid caused by differential heads; and, (7) uneven settlement caused by consolidation of material into voids.

Factors affecting the rate and extent of decomposition and stabilization in a landfill are also diverse and include temperature, waste composition, degree of compaction, moisture present, the rate of water movement, and the presence of inhibiting materials. With normal operations, the rate of decomposition within a landfill, as measured by gas production, reaches a maximum in about two years, and then gradually decreases to a level of stability where further degradation is essentially unnoticeable. However, the total stabilization process may take as long as 25 years or more.

The organic materials contained in landfilled wastes range from readily biodegradable substances, such as food wastes, to more refractory items, such as plastics, rubber and leather. A recently published article gave the following typical composition of municipal solid waste:

Table 1 Typical Physical Composition of Municipal Solid Wastes (Keegan, Hazardous Waste Management, May, 1989)

Component	Percent by weight (wet basis)
Food wastes	8.1
Paper and Cardboard	37.1
Plastics	7.2
Textiles	2.1
Rubber and Leather	2.5
Garden trimmings	17.9
Wood	3.8
Glass	9.7
Metals	9.6
Dirt, ashes, brick, etc.	1.9

Initially, refuse decomposition proceeds aerobically, utilizing oxygen from the air trapped within the refuse during filling. Upon depletion of this oxygen supply, which will likely occur relatively rapidly, decomposition continues anaerobically, yielding final gaseous endproducts of carbon dioxide (CO_2) and methane (CH_4).

In considering the natural course of microbially-mediated landfill stabilization, Pohland, et al., (1983) have proposed a useful means of description in terms of a series of typical phases which occur at some time during the "life" of each landfill. These phases are each characterized by leachate and gas compositions, as well as gas production rates, which typify the current landfill "age" or degree of stabilization. Using these descriptive phases, a better understanding of the conditions of a landfill and insights regarding the sequential changes in leachate and gas production and quality can be obtained. Such an approach is particularly useful in predicting the potential pollution potential of a landfill and its capability of producing methane gas in quantity sufficient for possible energy recovery and utilization.

Pohland, et al., (1983) described five phases of landfill stabilization as characterized below and depicted graphically in Figure 1.

Phase I: Initial Adjustment

- Initial waste placement and preliminary moisture accumulation.

- Initial subsidence and closure of each landfill area.

- Changes in environmental parameters are first detected to reflect the onset of stabilization

processes which are trending in a logical fashion.

Phase II: Transition

- Field capacity is exceeded and leachate is formed.

- A transition from initial aerobic to anaerobic microbial stabilization occurs.

- The primary, terminal electron acceptor shifts from oxygen to nitrates and sulfates, with the displacement of oxygen by carbon dioxide in the gas.

- A trend toward reducing conditions is established.

- Measurable intermediates, such as volatile organic fatty acids, first appear in the leachate.

Phase III: Acid Formation

- Intermediary volatile organic fatty acids become predominant with the continuing hydrolysis and fermentation of waste and leachate constituents.

- A precipitous decrease in pH occurs with a concomitant mobilization and possible complexation of metal species.

- Nutrients such as nitrogen and phosphorous are released and utilized in support of the growth of biomass commensurate with the prevailing substrate conversion rates.

- Hydrogen may be detected and affect the nature and type of intermediary products being formed.

Phase IV: Methane Fermentation

- Intermediary products appearing during the acid formation phase are converted to methane and excess carbon dioxide.

- The pH returns from a buffer level controlled by the volatile organic fatty acids to one characteristic of the bicarbonate buffering system.

- Oxidation-reduction potentials are at their most negative values.

- Nutrients continue to be consumed.

- Complexation and precipitation of metal species proceed.

- Leachate organic strength is dramatically decreased in correspondence with increases in gas production.

Phase V: Final Maturation

- Relative dormancy following active biological stabilization of the readily available organic constituents in the waste and leachate.

- Nutrients may become limiting.

- Measurable gas production all but ceases.

- Natural environmental conditions become reinstated.

- Oxygen and oxidized species may slowly reappear with a corresponding more positive oxidation-reduction potential.

- More microbially resistant organic materials may be slowly converted with the possible production of humic-like substances capable of complexing with and re-mobilizing heavy metals.

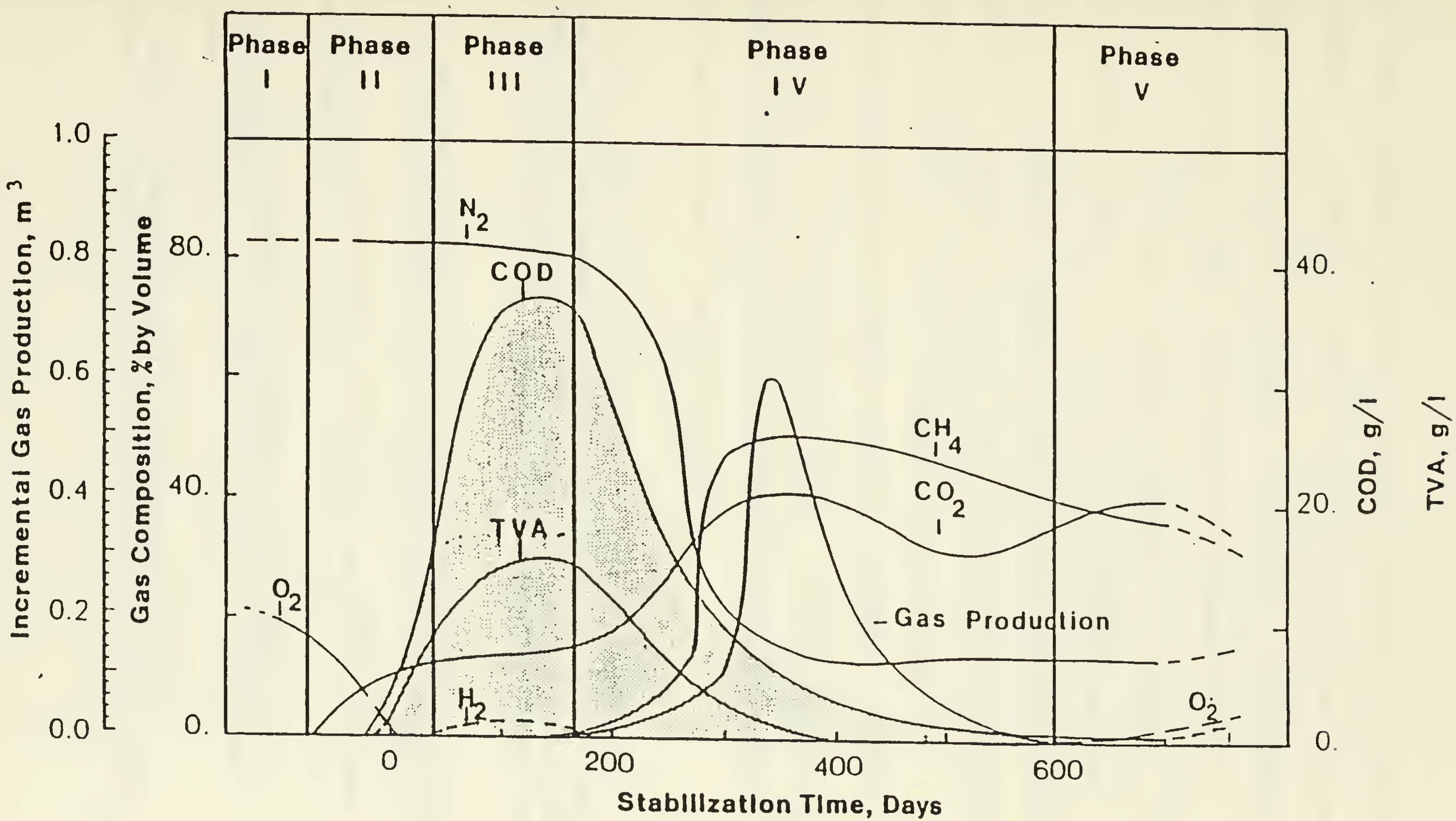


Figure 1 Changes in Selected Indicator Parameters During the Phases of Landfill Stabilization (Pohland, et al., 1983)

The Use of Leachate Recirculation through the Refuse Mass as a Management Option

As mentioned earlier, landfill stabilization is generally a slow process. However, the introduction of the innovative management strategy of leachate collection, containment and recycle (Pohland, 1975) permitted the operation of a landfill as a controlled system similar in concept to a large anaerobic reactor. Pilot-scale studies making direct comparisons between landfill operation with single pass leaching and leachate recycle have provided consistently convincing evidence of accelerated stabilization in landfills employing leachate recycle (Pohland, 1975 a, b; Pohland, *et al*., 1979, 1986 and 1987). Such beneficial leachate recirculation with increased contact between the leachate and the waste matrix provides:

- More effective utilization of the landfill's assimilative capacity for the attenuation of both hazardous and non-hazardous contaminants and enhanced protection against adverse environmental impacts.

- Improved homogeneity of the biochemical environment necessary for efficient anaerobic waste degradation.

- More process control through leachate and gas management.

- *In situ* leachate treatment with reduction or elimination of ultimate treatment or disposal requirements.

- Lower overall landfill management costs, beneficiated by the potential for energy recovery.

One full-scale operating sanitary landfill which is currently attempting this leachate management strategy is the Central Solid Waste Facility at Sandtown, DE, USA. At this facility, leachate recycle has been used at a 9- and 17.5-acre landfill site. Some operational difficulties at the initial site (9-acre site) led to improvement of the design of the second site (17.5-acre site) (Vasuki, 1987). Favorable experiences at the Sandtown facility are continuing to provide useful information regarding the requirements for successful operation of full-scale leachate recirculation systems.

Codisposal of Hazardous Wastes with Municipal Solid Wastes.

While the benefits of leachate recirculation at a sanitary landfill have been sufficiently well established, the effects of codisposal of hazardous constituents has been the subject of limited investigation. Since the goal herein is to propose a hazardous waste loading strategy for codisposal sanitary landfills operating with leachate recycle, an effort was made to extract from previous studies information that could be used to more clearly define the effects of hazardous constituent types, quantities and methods of application on the natural biodegradation of municipal solid wastes. Although only two of the studies examined employed leachate recycle, the

others provide additional and useful conclusions regarding codisposal, even though experiments were conducted under single pass leaching conditions.

Landfill codisposal has been practiced for some time in the United Kingdom, where 90% of the 100 million metric tons of hazardous wastes generated by industry are codisposed with municipal refuse in landfills. These landfills are required to have an impermeable clay liner with leachate containment, but are not required to have multiple liners and leachate collection as in the United States (Pirages, 1987). The following citations are representative of codisposal practices in the United Kingdom, as augmented by previous studies supportive of this research initiative.

Blakey, (1988)

As reported by Blakey (1988), a national program of research into codisposal was initiated by the United Kingdom Department of the Environment in 1973. The program included field investigations at 20 full-scale landfills receiving both industrial and domestic solid waste, laboratory and pilot-scale experimental studies of the effects of codisposal on the composition of landfill leachate, and lysimeter studies to investigate possible

attenuation mechanisms. While none of this work examined leachate recycle, conclusions regarding the natural attenuation mechanisms of sanitary landfills are interesting and pertinent.

From the field studies of the 20 existing codisposal sites, codisposal experiments and lysimeter studies, it was concluded that, under unsaturated hydrogeologic conditions, numerous attenuation mechanisms were operative. These mechanisms included:

- Immobilization of heavy metals
- Degradation of organic compounds
- Dilution due to dispersion
- Absorption of oils by cellulose in the wastes
- Enhanced biodegradation within the waste mass
- Precipitation of insoluble heavy metal sulfides
- Hydrolysis of cyanide
- Base exchange
- Sorption

A major conclusion from these combined studies was that "controlled landfilling in suitable hydrogeological environments and the selected codisposal of industrial and municipal wastes were acceptable practices." (Blakey, 1988)

<u>Pohland and Gould, (1986)</u>

During a 2-year pilot-scale simulated landfill study at the Georgia Institute of Technology, the fate and effect of heavy metals codisposed with municipal refuse, under leachate recycle operation, were investigated. Four cylindrical lysimeters, 4.27 meters high by 0.92 meter in diameter, were constructed of epoxy-lined corrugated steel pipe, and were each loaded with 400 kg of bulk municipal refuse. Three test columns also received 33.6 kg, 65.8 kg and 135.1 kg of a hydroxide metal sludge, respectively, while the fourth column served as a control, loaded only with refuse. To facilitate handling, the industrial metal plating sludge was mixed with 37.3 kg of sawdust. This sludge/sawdust mixture was placed into the simulated landfills in successive layers with the refuse, resulting in a relatively homogeneous sludge/refuse mixture. The final average compacted density within the columns was 233 kg/m^3 (wet basis). Based upon the sludge and refuse characteristics reported by Pohland and Gould, (1986), the inorganic pollutant loadings applied were calculated and are presented in Table 2.

Table 2 Inorganic Pollutant Loadings to Simulated Landfills (Pohland and Gould, 1986)

	Metal Concentration (g metal/kg dry, bulk refuse)					
Column	Zn	Cr	Ni	Cd	Cu	Fe
1 (control)	-	-	-	-	-	-
2	26.6	1.8	0.034	1.1	0.015	7.9
3	52.2	3.5	0.066	2.2	0.031	15.5
4	107.2	7.1	0.14	4.4	0.062	31.8

During the study, leachate recycle operation (quantity and frequency) and water addition, as influenced by climatic conditions, were described in terms of five operational phases (Table 3).

Pohland and Gould, (1986) reported that the two heavier loaded columns (3 and 4) indicated distinct evidence of microbial inhibition, as was characterized by the various test parameters. In contrast, most leachate characteristics of Column 2, the lightest loaded column, were very similar to those for Column 1, the control column.

Table 3 Operational Phases of Simulated Landfill Study (Pohland and Gould, 1986)

Operational Phase	Time Since Loading (Days)	Description
A	0-200	Facile production of leachate and washout
B	200-380	Initial microbially-mediated stabilization
B '	380-480	No leachate production or recycle (period of drought)
C	480-600	Postdrought resumption of leachate production and stabilization
D	600-720	Terminal phase of leachate production and stabilization

Leachate COD concentrations measured during the four principal operational phases (Figure 2) indicated an initial, rapid washout from all four columns, followed by a period of decreasing concentration for Columns 1 and 2 as stabilization progressed, finally reaching a constant level. Variations in COD concentrations observed for Columns 3 and 4 were believed to be suggestive of a possible cyclic process which may have resulted as these columns experienced alternating periods of toxicity/inhibition and acclimation to the heavy metals present. However, the overall effect of the higher metal loadings in Columns 3 and 4 was clearly that of inhibition,

as evidenced by the elevated leachate COD concentrations in the latter two phases of the study.

Leachate total volatile acids (TVA) data (Figure 3) further supported the conclusion that the highest loaded columns (3 and 4) experienced definite toxic effects. Column 1 first showed a rapid decrease from initially high leachate TVA levels and then stabilized at a lower level as the process of rapid volatile acid formation and consumption proceeded smoothly during the project period. Leachate TVA concentrations for Column 2 followed a very similar, yet delayed pattern, while those for Columns 3 and 4 showed an inability to biologically convert the volatile acids to methane and carbon dioxide. In reviewing the TVA data, inhibitory effects may have had a greater adverse influence upon methanogenesis, since volatile acids concentrations for Columns 3 and 4 appeared in significant amounts, yet their conversion to methane and carbon dioxide was relatively very limited.

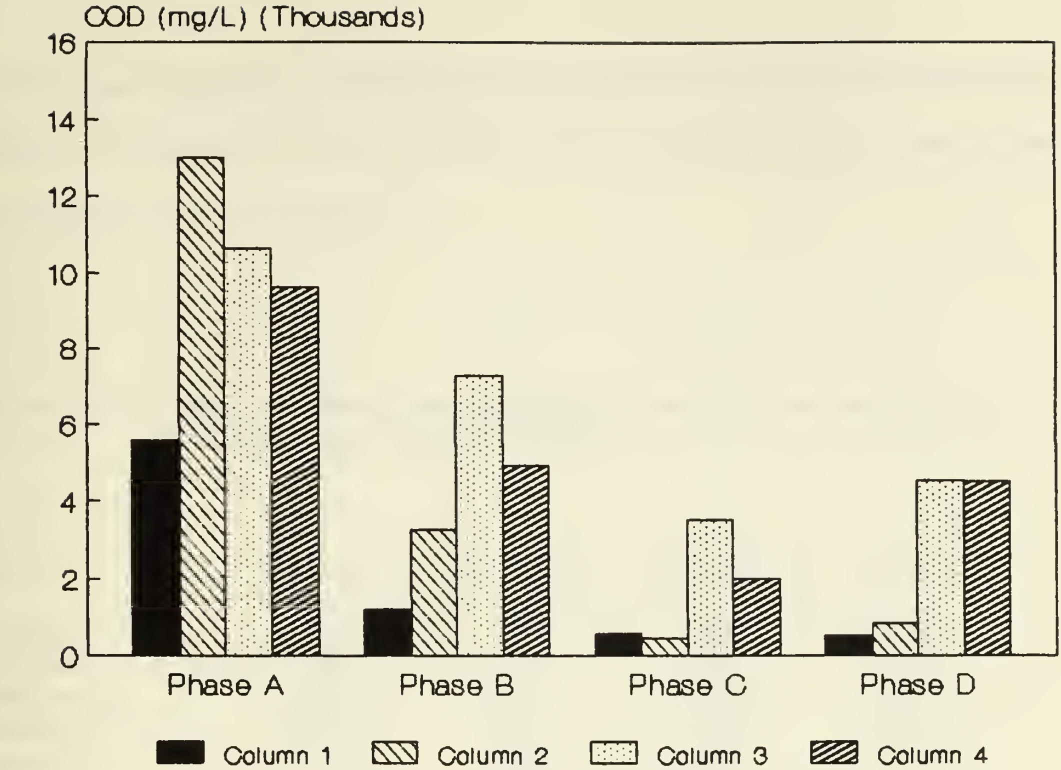


Figure 2 Average Leachate COD Concentrations (Pohland and Gould, 1986)

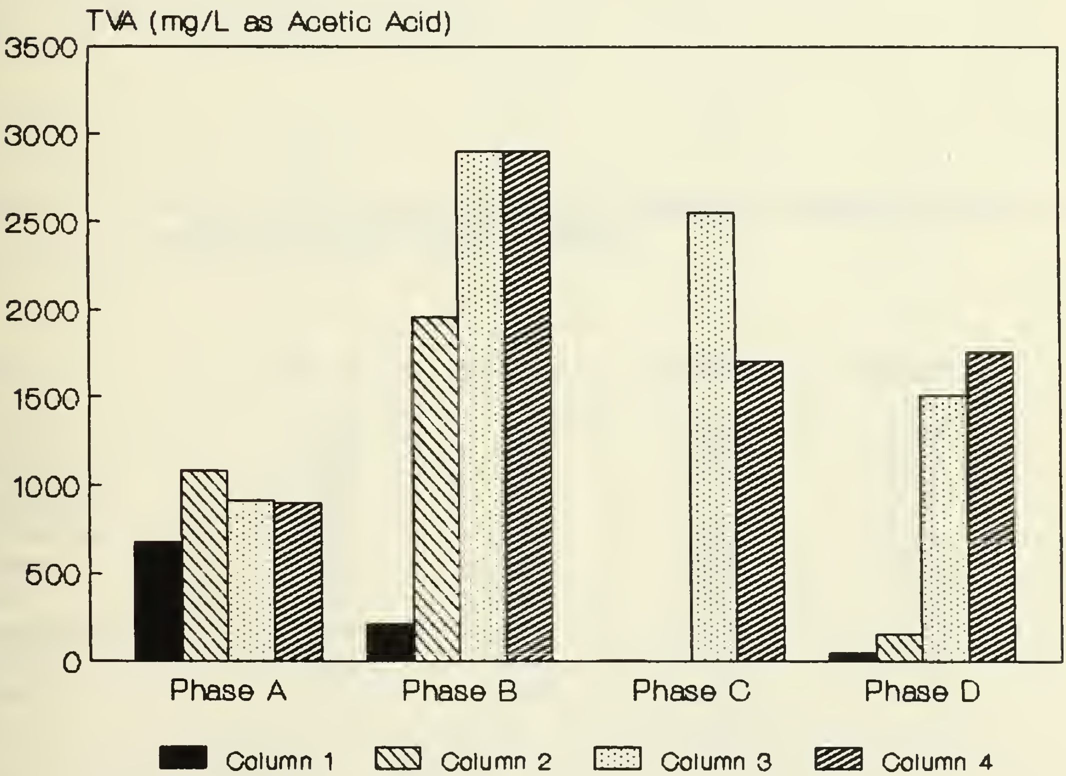


Figure 3 Average Leachate TVA Concentrations (Pohland and Gould, 1986)

The average metal concentrations measured in the leachate samples during the four operational phases are summarized in Tables 4, 5, 6 and 7.

Table 4 Phase A- Average Leachate Metal Concentrations (mg/L) (Pohland and Gould, 1986)

Metal	Column 1	Column 2	Column 3	Column 4
Sodium	660	770	950	940
Calcium	380	400	380	324
Cadmium	BDL	3.1	2.5	6.3
Chromium	BDL	0.2	BDL	BDL
Copper	BDL	BDL	BDL	BDL
Iron	54	76	96	69
Manganese	7.9	9.0	6.6	8.4
Nickel	<0.1	0.9	0.5	0.9
Zinc	0.8	367	155	323

BDL = below detection limit

Table 5 Phase B- Average Leachate Metal Concentrations (mg/L) (Pohland and Gould, 1986)

Metal	Column 1	Column 2	Column 3	Column 4
Sodium	320	360	400	398
Calcium	270	320	240	233
Cadmium	BDL	0.2	1.1	0.5
Chromium	BDL	0.4	BDL	0.1
Copper	BDL	BDL	BDL	BDL
Iron	41	41	124	74
Manganese	5.0	2.9	4.3	3.8
Nickel	0.1	0.4	0.6	0.6
Zinc	0.2	40	118	81

BDL = below detection limit

Table 6 Phase C- Average Leachate Metal Concentrations (mg/L) (Pohland and Gould, 1986)

Metal	Column 1	Column 2	Column 3	Column 4
Sodium	443	474	433	647
Calcium	431	456	662	731
Cadmium	BDL	0.1	0.4	0.2
Chromium	BDL	BDL	BDL	BDL
Copper	BDL	BDL	BDL	BDL
Iron	60	53	57	63
Manganese	2.6	0.8	2.2	2.4
Nickel	0.2	0.2	0.5	0.5
Zinc	2.5	30	88	85

BDL = below detection limit

Table 7 Phase D- Average Leachate Metal Concentrations (mg/L) (Pohland and Gould, 1986)

Metal	Column 1	Column 2	Column 3	Column 4
Sodium	488	520	503	558
Calcium	453	426	794	715
Cadmium	BDL	0.1	0.3	0.4
Chromium	BDL	BDL	BDL	BDL
Copper	BDL	BDL	BDL	BDL
Iron	74	68	136	116
Manganese	2.1	0.7	3.5	4.0
Nickel	0.2	0.3	0.8	1.0
Zinc	1.8	34	132	157

BDL = below detection limit

The fact that Pohland and Gould, (1986) found that all the organic parameters studied exhibited similar trends led them to conclude that, while Column 2 showed only limited

evidence of inhibition or toxicity, the sludge loadings in Columns 3 and 4 were sufficient to overwhelm the assimilative capacity of those landfill columns for the metal sludge, thereby resulting in toxicity to the natural microbially-mediated waste stabilization processes.

The inherent assimilative capacity for the heavy metals within the simulated landfills were believed to arise from several mechanisms. Zinc, cadmium and nickel levels were either low (< 2.5 mg/L Zn, and < 0.2 mg/L Ni), or below detection limit (Cd) in the leachate from Column 1. But, an initial washout, followed by significant attenuations of readily mobilized metals, was observed in the leachate of Column 2 and, to a much lesser extent, in the leachates from Columns 3 and 4. In the last phase of the study period, an increase in leachate metal concentrations indicated some degree of remobilization of those metals, the cause of which was proposed to be complexation with humic-like substances.

Also with regard to assimilative mechanisms, precipitation as metal sulfides was indicated as important for the removal of Zn, Cd, Ni and Fe, while the only significant Cr precipitate was that of its hydroxide, ($Cr(OH)_3$). Additionally, experimental evidence suggested the formation of metal carbonates, which may have effectively encapsulated the toxic metal hydroxides within a less

soluble barrier of metal carbonates, thus reducing the potential mobility of the toxic metals. Leachate recirculation was thought to enhance this encapsulation, through the increased intimate contact between the leachate and sludge.

Resulting from these various attenuation mechanisms, the leachate metal concentrations were decreased. In the case of Column 2, these mechanisms have apparently lowered the metal concentrations below some toxic threshold levels that were not attained in Columns 3 and 4. Thus, under the operational conditions of this experiment, one or more metal loading threshold was exceeded as the metal loadings were increased between Columns 2 and 3 (Table 2). Within this range of loadings the assimilative capacity of the experimental landfill system was exceeded to the extent that residual leachate metal concentrations significantly retarded microbial activity.

Pohland, Schaffer, Yari and Cross, (1987)

In a 450-day laboratory-scale simulated landfill study, Pohland, et al., (1987), investigated the fate of 12 selected organic priority pollutants codisposed with shredded municipal solid waste. Four 208-liter high-density polyethylene (HDPE) tanks were loaded and operated

in duplicate pairs. One pair was operated with leachate recycle (Cells 1 and 2), while the other set incorporated single pass leaching (Cells 3 and 4). Each cell received 82 kg (wet) of shredded municipal refuse in a 170-liter volume, resulting in a final compacted density of 480 kg (wet)/m^3 (360 kg (dry)/ m^3). On Day 30 (30 days after field capacity was attained), Columns 2 and 4 were spiked with approximately 600 milligrams (mg) each of ten organic pollutants for a loading of 10 mg pollutant/kg shredded refuse (dry). Two polychlorinated biphenyls (PCBs) were spiked in lesser amounts of 75 mg per cell due to their relatively high cost.

Addition of the organic priority pollutants to Cells 2 and 4 was accomplished by placing the organic contaminants into solutions and then applying these solutions to the refuse. The method of preparation and the specific contents of these solutions are summarized in Table 8.

Initially, six liters of deionized water were added weekly to all four cells, an equivalent of 127.0 cm per year. This moisture application rate continued throughout the 450-day study period for the single pass reactors (Cells 3 and 4), but on Day 37, water addition to the recycle cells was discontinued, as leachate volumes accumulated in amounts adequate to accommodate recycling and sampling throughout

the remainder of the project period.

Table 8 Organic Priority Pollutant Spikes (Pohland, et al., 1987)

	Cell 2	Cell 4
Solution 1:		
2,6-dinitrotoluene	600.15 mg	600.35 mg
2,4-dinitrotoluene	594.45 mg	593.55 mg
di-n-butyl phthalate	609.08 mg	605.70 mg
Dissolve in about 8 mL of methanol. Then dilute with 1 L of deionized water.		
Solution 2:		
phenol	603.30 mg	604.92 mg
pentachlorophenol	600.20 mg	601.60 mg
4,6-dinitrocresol	540.90 mg	539.46 mg
Dissolve in about 8 mL of methanol. Then dilute with 1 L of deionized water.		
Solution 3:		
methylethylketone	648.75 mg	595.80 mg
trichloroethylene	602.60 mg	600.40 mg
hexachloroethane	602.15 mg	599.35 mg
Dissolve in about 5 mL of methanol. Then dilute with 1 L of deionized water.		
Solution 4:		
phenanthrene	600.06 mg	600.06 mg
Dissolve in about 100 mL of hexane. Then, while stripping the hexane with N_2 gas, dissolve in acetone. Then dilute with 1.5 L of deionized water.		

Table 8 (continued)

	Cell 2	Cell 4
Solution 5:		
2,4' -dichlorobiphenyl	75.00 mg	75.00 mg
hexachlorobiphenyl	75.00 mg	75.00 mg

Dissolve in about 50 mL of hexane. Then, while stripping the hexane with N_2 gas, dissolve in acetone. Then dilute with 0.5 L of deionized water.

To facilitate initiation of methane fermentation, supernatant from an anaerobic sludge digester was obtained from the R. M. Clayton Wastewater Treatment Plant in Atlanta, GA and was applied to all four cells on Days 209, 219, 226 and 238. Because of apparent inhibition due to low leachate pH, 1.5 N sodium carbonate added to raise the leachate pH to 6.5. The combination of sludge seeding, pH adjustment and temporarily lowering the leachate recycle rate schedules led to the establishment of viable methanogenesis on about Day 304. After Day 304, the columns were operated without further pH adjustments and recycle rates were nearly 25 liters per week; the same rate used during the acid formation phase of stabilization. Since the test cells were contained within a laboratory with temperatures between 29 and 35 ^{o}C, optimum mesophilic anaerobic digestion temperatures (Metcalf and Eddy, 1979) prevailed.

Leachate samples were collected and analyzed weekly for gross parameters, metals and trace organic priority pollutants. None of the spiked priority pollutants were detected in any of the leachate samples from any of the cells. Therefore, it was concluded that the spiked organics were either removed within the landfill cells through physical-chemical assimilation or bioconversion, and that possible partitioning through the refuse mass was exceedingly slow and not complete at the termination of the study. In addition, no inhibition by the organic priority pollutant loadings to the simulated landfills was detected. These facts demonstrated the significant assimilative capacity of a landfill for organic priority pollutants. Pohland, et al., (1987) attributed this assimilative capacity to various in situ attenuation mechanisms including sorption, bioconversion and complexation. As the finite assimilative capacity for the selected organics could not be determined through this study, the final recommendation was for additional studies on allowable loadings in codisposal facilities. The present study examines both the fate of organic and inorganic priority pollutants codisposed with municipal refuse in simulated landfills operating with leachate recycle or single pass leaching.

Chapter III: Methods and Materials

Lysimeter Construction and Loading

The purpose of this experiment was to investigate the behavior and fate of selected organic and inorganic toxic priority pollutants codisposed with shredded municipal refuse. To accomplish this, ten pilot-scale simulated landfill columns were constructed on the Georgia Institute of Technology campus. Five of these lysimeter columns were constructed to operate with leachate containment, collection and recycle, while the remaining five were built to operate in a single pass leaching mode.

The columns were loaded as identical pairs, one recycle and one single pass column, to facilitate evaluation of the expected benefits of leachate recycle. All pairs received equal quantities of shredded municipal refuse. One pair served as the controls and, therefore, were not spiked with any priority pollutants. The remaining four pairs were all spiked with equal quantities of selected organic priority pollutants, with three pairs receiving additional, but varying, loadings of inorganic pollutants in the form of a heavy metal sludge mixture. Table 9 summarizes the loadings and operation of the simulated landfill columns.

Table 9 Lysimeter Operational Modes and Loadings

Column No. and (Code)*	Mode of Operation	Priority Pollutants Added: Organics	Priority Pollutants Added: Inorganics
1 (CR)	Recycle	None	None
2 (CS)	Single pass	None	None
3 (OS)	Single pass	Yes	None
4 (OLS)	Single pass	Yes	Low
5 (OMS)	Single pass	Yes	Medium
6 (OR)	Recycle	Yes	None
7 (OLR)	Recycle	Yes	Low
8 (OHS)	Single pass	Yes	High
9 (OMR)	Recycle	Yes	Medium
10 (OHR)	Recycle	Yes	High

*Codes:

CR = Control recycle
CS = Control single pass
OS = Organics, single pass
OLS = Organics, low metals, single pass
OMS = Organics, medium metals, single pass
OR = Organics, recycle
OLR = Organics, low metals, recycle
OHS = Organics, high metals, single pass
OMR = Organics, medium metals, recycle
OHR = Organics, high metals, recycle

The column designs accommodated the two described modes of leachate management, and ancillary equipment provided the means to monitor ambient temperature, column temperature (within the refuse), leachate generation, and gas quality and quantity. Located in a high-bay laboratory area (Figure 4), the columns had the design features illustrated in Figures 5 and 6, which depict typical Single Pass and Leachate Recycle columns, respectively.

[illegible]

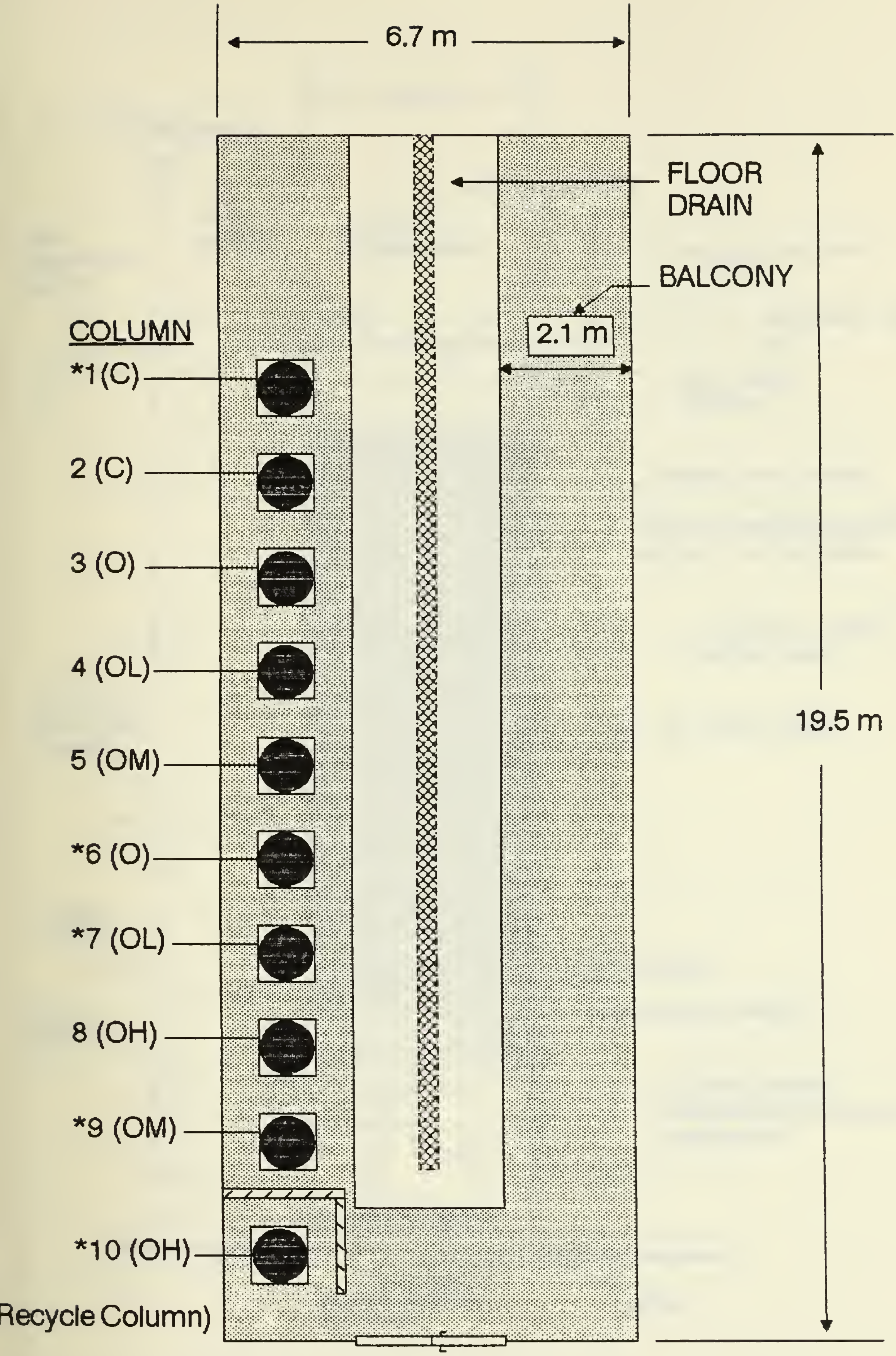


Figure 4 Location Plan for Landfill Simulators in High-Bay Area (Not to Scale)

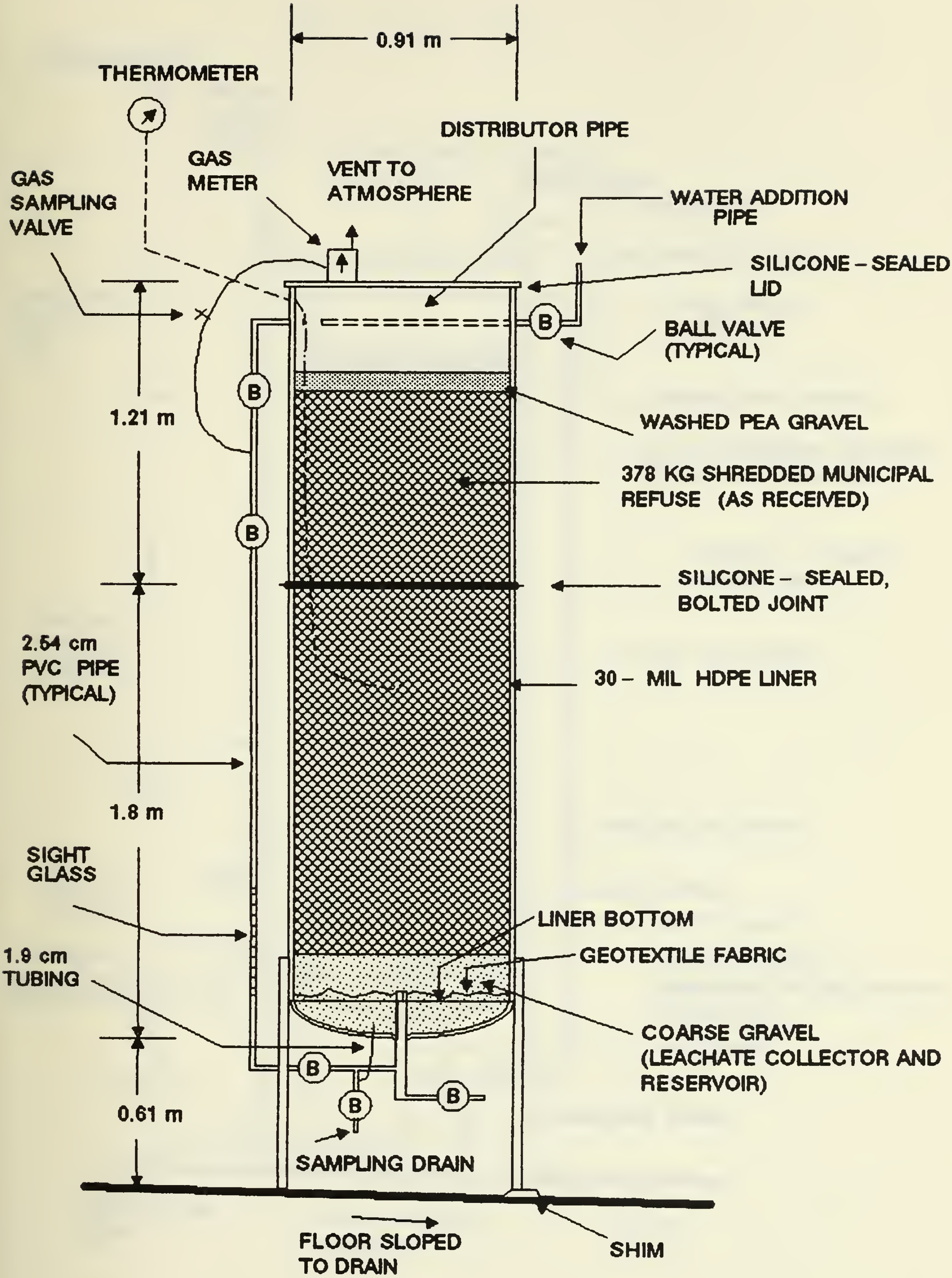


Figure 5 Single Pass Lysimeter (Not to scale)

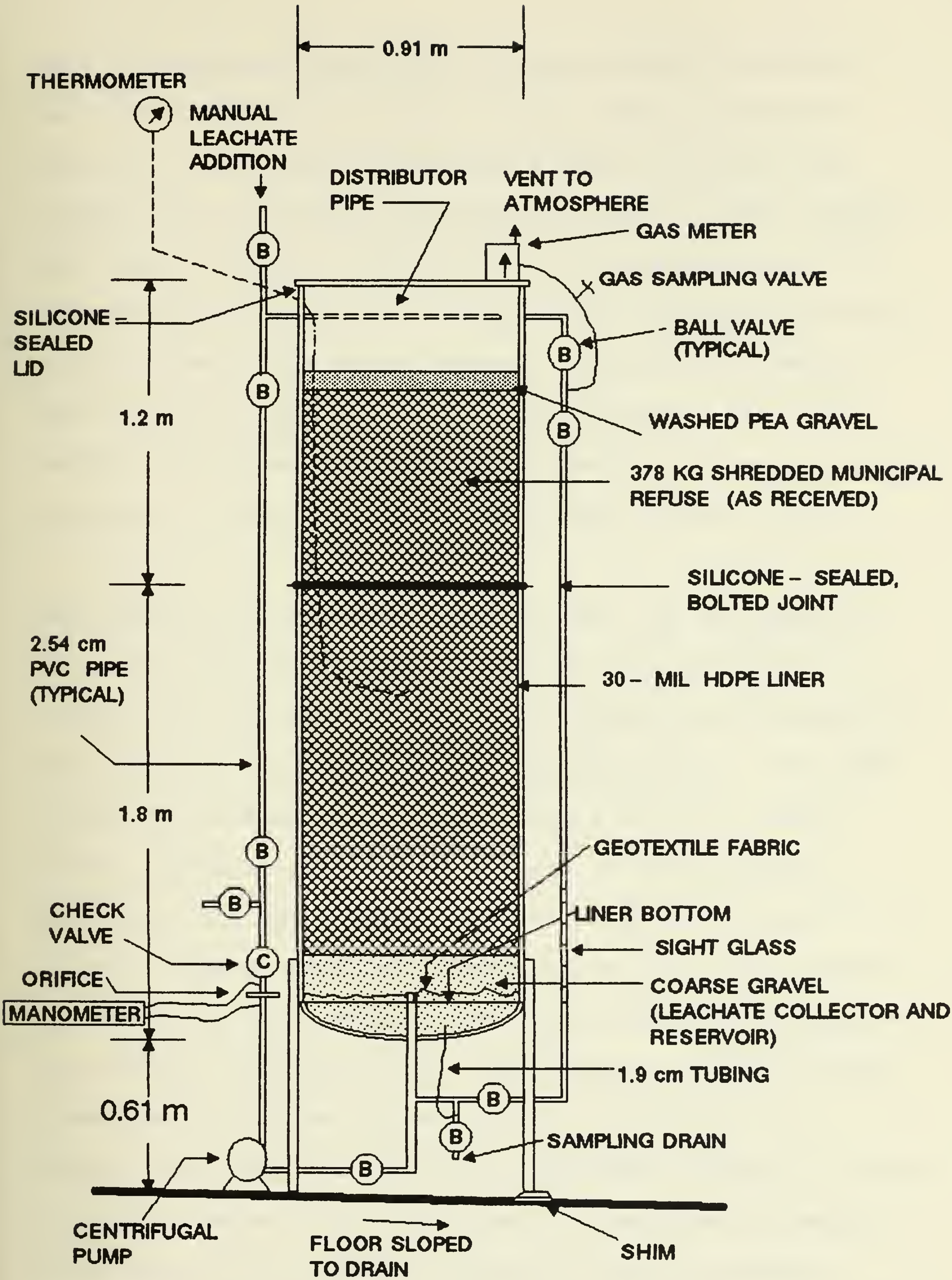


Figure 6 Leachate Recycle Lysimeter (Not to scale)

Made of 20-gauge steel, nine of the simulated landfills were constructed by bolting 1.2-meter long cylindrical sections to the tops of previously used 1.8-meter high columns that had been refurbished for use in these studies. The tenth column was identical in size and features, but fabricated separately for the project. During construction of the columns, the joints between sections were sealed water and gas tight with a silicone sealant. Also, to inhibit corrosion and/or leaching from the column structures, a primer coat was applied to the interior metal surface.

High density polyethylene (HDPE) liners (by Poly-America, Inc.) were fabricated for the columns and installed to contain the leachate and facilitate removal and analysis of the refuse at the conclusion of the experiment. The HDPE liners were placed above approximately 30 cm of coarse gravel. After installation, a layer of coarse gravel, about 10 to 20 cm in depth, was placed at the bottom of the columns to serve as both a leachate reservoir and a means to screen the above refuse, thereby preventing clogging of the leachate collector pipe. The leachate collector pipe penetrated the column liner to permit withdrawal of leachate for recycle, discard or sampling. However, during operation, leaks in the liner were detected and prompted the addition of a leachate collection line to capture leachate accumulated within the annular space between the metal column and the HDPE liner. Figures 5 and 6

illustrate this 1.9-cm plastic line.

Uncompacted, shredded municipal refuse, of domestic origin, was received from the DeKalb County, GA shredding facility and was then sampled and weighed immediately prior to loading into the columns. Analysis of eight samples, obtained from different portions of the refuse, indicated refuse characteristics shown in Table 10.

Placement of the refuse in each lysimeter was accomplished by manually loading five to six 9-kg batches of refuse into the column and then compacting in-place with a hand tamper. Each column received a total of 42 individual 9-kg batches of refuse within a period of about eight hours, for a total of 378 kg refuse (as-received) in each simulated landfill. Loading of the priority pollutants within the waste, in the applicable columns, was performed simultaneously, in the manner described subsequently.

Upon completion of the loading process, an 8-cm layer of washed pea gravel was placed on top of the refuse to aid in the even distribution of moisture applied through the perforated distributor pipe located above the gravel.

Once loaded, the lysimeters were sealed, thereby providing positive control over the moisture balance and allowing the

[illegible]

direct and continuous measurement of gas production. The simulated landfill columns were loaded in one day (18 September 1985) and were sealed on the following day, at which time tap water additions commenced to bring the columns to field capacity. Monitoring of gas production and temperature also began the day after loading.

Table 10 Characteristics of Refuse Used in Loading the Simulated Landfill Columns

Sample No.	Moisture Content (%)	Calorific Value (cal/g)*	Ash Content (%)*	Elemental Content (%)* C	H	N
1a	27.3	4422	19.3	35.0	7.6	BDL**
1b	26.9	4272	14.2	40.0	5.2	5.1
2a	33.5	4835	13.5	36.0	5.3	0.7
2b	29.5	4654	13.4	36.0	5.0	0.7
3a	26.1	4279	10.8	40.0	5.3	1.5
3b	26.5	4458	15.9	39.0	5.3	0.9
4a	27.2	-	19.0	48.0	7.0	0.9
4b	27.8	-	14.1	47.0	6.8	0.9
5a	27.9	4318	14.4	38.0	5.3	2.7
5b	29.2	4494	16.4	40.0	5.9	0.9
6a	28.7	4376	13.6	37.0	4.8	BDL**
6b	26.2	4377	10.5	41.0	5.3	0.9
7a	35.0	4192	15.6	37.0	5.3	1.8
7b	32.0	4402	13.0	41.0	5.9	4.5
8a	39.2	4264	17.9	38.0	5.3	0.9
8b	38.1	4379	13.7	39.0	5.0	0.9

* Dry weight basis
** BDL = below detection limit

The types of priority pollutants spiked were chosen to be representative of common organic and inorganic toxic hazardous substances. The quantities of inorganic contaminants spiked were chosen at levels where total or severe inhibition was not expected to occur. Previous work (Pohland and Gould, 1986) was used to estimate some of these quantities. As discussed in Chapter II, suggested threshold levels for the toxic metals zinc, cadmium, and copper are, respectively, 26.6, 1.1 and 0.015 g metal/kg bulk refuse (dry basis). Copper was not spiked in the present experiment, but the addition of small quantities of mercury and lead, two other common toxic metals, were included. Organic priority pollutant quantities were based upon anticipated concentration considerations, assimilative capacities, costs and analytical sensitivities.

Table 11 indicates the mass quantities, as well as the physical forms, of the organic priority pollutants added to each of the eight test columns, Columns 3 through 10. Columns 1 (CR) and 2 (CS) served as the respective recycle and single pass control columns, while the test columns received equal quantities of the organic pollutants. The organic contaminants were applied by spreading the pollutants over the refuse surface at a depth of 30 cm above the refuse bottom. The organics were then immediately covered with either sawdust, in the case of columns 3 (OS) and 6 (OR), or the inorganic pollutant

mixture, in the case of columns 4 (OLS), 5 (OMS), 7(OLR), 8 (OHS), 9 (OMR) and 10 (OHR), as described subsequently. In both instances, the continued placement of refuse followed the loading process.

Table 11 Organic Priority Pollutants Loaded in the Test Columns 3 through 8

Compound	Physical Form	Mass Loading (g)
Naphthalene	solid	120
Hexachlorobenzene	solid	120
2-Nitrophenol	solid	120
1, 2, 3, 4, 5, 6-Hexachlorocyclohexane (Lindane)	solid	120
Dieldrin	solid	30
2, 4-Dichlorophenol	solid	120
p-Dichlorobenzene	solid	120
Dioctyl phthalate	liquid	120
1, 2, 4-Trichlorobenzene	liquid	120
Dibromomethane	liquid	120
Nitrobenzene	liquid	120
Trichloroethylene	liquid	120

The organic compounds used in the loading were all reagent grade chemicals. Placement of the organic priority pollutants at this low depth within the column was desired to better ensure detection of these constituents during the early phases of the experiment, if not the entire study period.

The inorganic priority pollutants spiked in Columns 4 (OLS), 5 (OMS), 7 (OLR), 8 (OHS), 9 (OMR) and 10 (OHR) were in the form of carefully prepared mixtures of metal processing sludges, metal oxides and sawdust, the latter of which was added to facilitate replication of application. Industrial sludge sources included two metal plating facilities: Saft America, Incorporated (SAF), in Valdosta, GA and the Dixie Industrial Finishing Company (DIF) in Tucker, GA. To achieve the desired low, medium and high heavy metal loadings, two identical mixtures of each of these loadings were prepared. The compositions of these mixtures, (Table 12), were based upon analyses of the industrial metal sludges, given in Table 13, and the desired metal loadings.

Each inorganic pollutant sawdust mixture was added to the appropriate column by first dividing the mixture into three equal portions and then spreading each portion evenly onto the refuse surface, one at the 30 cm refuse depth (just above the organic pollutants), the second at the refuse mid-depth, and the third portion about 30 cm below the

Table 12 Industrial Sludge, Metal Oxide and Sawdust Loadings for Test Columns 4, 5, 7, 8, 9 and 10

Constituent (as received)	Loading Level: Low	Medium	High
DIF (kg)	5	10	20
SAF (kg)	0.8	1.6	3.2
Cr_2O_3 (g)	34	68	136
HgO (g)	22	44	88
PbO (g)	113	226	452
ZnO (g)	134	268	536
Sawdust (kg)	6	6	6

Table 13 Industrial Metal Sludge Characteristics

	Sludge Source: DIF*	SAF*
Moisture Content (%)	78.7	79.7
Total Volatile Solids (%)	18.5	14.6
Metals (g/kg dry sludge)		
Cadmium (Cd)	7.2	167
Chromium (Cr)	21.6	0.4
Mercury (Hg)	ND**	ND

Table 13 (continued)

	Sludge Source	
	DIF*	SAF*
Nickel (Ni)	0.3	459
Lead (Pb)	0.4	ND
Zinc (Zn)	45.4	0.3
Copper (Cu)	ND	ND
Iron (Fe)	204	2.3

* DIF = Dixie Industrial Finishing Company
SAF = Saft America, Incorporated
** ND = none detected

uppermost surface of the solid waste mass. In addition, 100-gram portions of the sludge/metal oxide/sawdust mixture were mixed with 50 cm^3 of Ottawa sand, contained in nylon bags, and then placed in the six columns receiving the inorganic hazardous waste loadings. Two "bags" were placed into each of these columns, one in the bottom (30 cm) layer, and the second in the top layer. It is intended that these samples will be recovered at the conclusion of the experiment to assess any surfacial changes to the contaminant mixtures. In comparison to the overall metal loadings, these "bags" constitute a negligible addition (< 2% by mixture weight) of contaminants.

With knowledge of the masses of contaminants applied, and

the results from the refuse and industrial sludge characterization analyses performed, the priority pollutant loadings can be calculated on a mass of pollutant per mass of dry refuse basis. The results of these calculations are summarized in Table 14. It is important to realize, however, that these mass loadings do not indicate the physical manner in which these substances were loaded into the landfill system, an important factor that is discussed in the "Results and Discussion" chapter of this report.

Immediately upon completion of the column loading and sealing operations, pressure tests were conducted to assure water and gas-tight seals, and water additions commenced to bring the simulated landfills to field capacity so that leachate production for recycle and analysis could be initiated immediately. Field capacity was reached approximately 30 days after loading. Gas quantity and column and ambient temperature measurements also began immediately after the columns were sealed. Thereafter, operation of the simulated landfills was largely based upon the behavior of the systems as natural microbially-mediated stabilization processes ensued.

Table 14 Priority Pollutant Loading per Column*

Pollutant	1(CR)	2(CS)	3(OS)	4(OLS)	5(OMS)	6(OR)	7(OLR)	8(OHS)	9(OMR)	10(OHR)
Inorganics:										
Cadmium	NONE	NONE	NONE	0.13	0.26	NONE	0.13	0.53	0.26	0.53
Chromium	NONE	NONE	NONE	0.17	0.35	NONE	0.17	0.7	0.35	0.7
Mercury	NONE	NONE	NONE	0.076	0.16	NONE	0.076	0.31	0.16	0.31
Nickel	NONE	NONE	NONE	0.28	0.56	NONE	0.28	1.1	0.56	1.1
Lead	NONE	NONE	NONE	0.4	0.8	NONE	0.4	1.6	0.8	1.6
Zinc	NONE	NONE	NONE	0.59	1.2	NONE	0.59	2.4	1.2	2.4
Organics:										
Naphthalene	NONE	NONE	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Hexachlorobenzene	NONE	NONE	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
2-Nitrophenol	NONE	NONE	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
1, 2, 3, 4, 5, 6-Hexachloro-cyclohexane (Lindane)	NONE	NONE	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Dieldrin	NONE	NONE	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
2, 4-Dichlorophenol	NONE	NONE	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
o-Dichlorobenzene	NONE	NONE	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Dioctyl phthalate	NONE	NONE	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
1, 2, 4-Trichlorobenzene	NONE	NONE	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Dibromomethane	NONE	NONE	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Nitrobenzene	NONE	NONE	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Trichloroethylene	NONE	NONE	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45

Column Identity applies to columns 1(CR) through 10(OHR).

* g pollutant/kg shredded municipal refuse, dry basis

Analytical Parameters and Methods

With field capacity attained approximately 30 days after loading, the resultant production of leachate allowed for the initiation of routine analysis and recycle of leachate. Analyses were regularly performed for the physical, chemical and biological parameters indicative of the phases of landfill stabilization, and to monitor the spiked priority pollutants. Included among the parameters reflective of the chemical environment within the simulated landfills were conductivity, pH, alkalinity and oxidation-reduction potential (ORP). The organic strength of the leachate was measured in terms of 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD) and total organic carbon (TOC). With the exception of trace organics analysis, the particular analyses performed, methods used, precision and accuracy are summarized in Table 15.

Table 15 Summary of Analyses, Methods, Precision and Accuracy

Measurement	Reference	Precision (Standard deviation)	Accuracy
Conductivity	EPA 600/4-79-020 Method 120.1	+/-6%	95-105%
pH	EPA 600/4-79-020 Method 150.1	+/-0.1 SU*	+/-0.1 SU

Table 15 (continued)

Measurement	Reference	Precision (Standard deviation)	Accuracy
Alkalinity	EPA 600/4-79-020 Method 310.1	+/-5%	95-105%
Cl^-, SO_4^{-2}, PO_4^{-3}, S^{-2}	Standard Methods for the Examination of Water and Wastewater, Method 429	+/-10%	90-110%
NH_3-N	EPA 600/4-79-020 Method 350.3	+/-5%	90-110%
ORP	ASTM Method 1498-99	-	-
BOD_5	EPA 600/4-79-020 Method 405.1	+/-20%	-
COD	EPA 600/4-79-020 Method 410.1	+/-10%	90-110%
TOC	EPA 600/4-79-020 Method 415.1	+/-10%	90-110%
CH_4, CO_2, H_2	Gas chromatography	+/-5%	90-110%
Cadmium	EPA 600/4-79-020 Methods 213.1 & 213.2	+/-10%	90-110%
Calcium	EPA 600/4-79-020 Method 215.1	+/-5%	90-110%
Chromium	EPA 600/4-79-020 Methods 218.1 & 218.2	+/-10%	90-110%
Iron	EPA 600/4-79-020 Method 236.1	+/-10%	90-110%
Lead	EPA 600/4-79-020 Methods 239.1 & 239.2	+/-10%	90-110%
Magnesium	EPA 600/4-79-020 Method 242.1	+/-5%	90-110%

Table 15 (continued)

Measurement	Reference	Precision (Standard deviation)	Accuracy
Manganese	EPA 600/4-79-020 Methods 243.1 & 243.2	+/-10%	90-110%
Mercury	EPA 600/4-79-020 Method 245.1	+/-20%	80-120%
Nickel	EPA 600/4-79-020 Methods 249.1 & 249.2	+/-10%	90-110%
Potassium	EPA 600/4-79-020 Method 258.1	+/-5%	90-110%
Sodium	EPA 600/4-79-020 Method 273.1	+/-5%	90-110%
Zinc	EPA 600/4-79-020 Methods 289.1 & 289.2	+/-10%	90-110%
Lithium	Standard Methods, 16th Ed., Method 317B	+/-5%	95-105%
Solid Waste Calorific Value	Parr Instruments Tech. Manual #130	-	-
Solid Waste Moisture	Ohaus Instruments Tech, Manual	+/-%5	90-110%
Volatile Organic Acids	Direct Aqueous Injection Capillary Column, Gas Chromatography	+/-10%	90-110%

*SU = standard units

In the absence of existing standard protocols for the analysis of trace organic pollutants in leachates, an analytical scheme was developed, after consulting various other methods of analysis, including:

"Methods for Organic Pesticides in Water and Wastewater," 1971, U.S. EPA, Environmental Research Center, Cincinnati, OH 45268

"The Determination of Volatile Organic Compounds at the microgram per liter Level in Water by Gas Chromatography," 1974, U.S. EPA, Environmental Research Center, Analytical Quality Control Laboratory, Cincinnati, Oh 45268

"Method for Organochlorine Pesticides in Industrial Effluents," 1973, U.S. EPA, Environmental Research Center, Analytical Quality Control Laboratory, Cincinnati, OH 45268

"Method for Polychlorinated Biphenyls (PCBs) in Industrial Effluents," 1973, U.S. EPA, Environmental Research Center, Analytical Quality Control Laboratory, Cincinnati, OH 45268

"Sampling and Analysis Procedures for Screening of Industrial Effluents for Priority Pollutants," April 1977, U.S. EPA, Environmental Monitoring and Support Laboratory, Cincinnati, OH 45268

"The Analysis of Trihalomethanes in Finished Waters by the Purge and Trap Method," September, 1977, U.S. EPA, Environmental Monitoring and Support Laboratory, Cincinnati, OH 45268

In the analytical scheme developed, leachate samples were extracted for four hours with methylene chloride using a continuous vapor phase procedure. The samples were then dried over anhydrous sodium sulfate, concentrated to a volume of 1.0 to 4.0 mL in a Kuderna-Danish apparatus, and

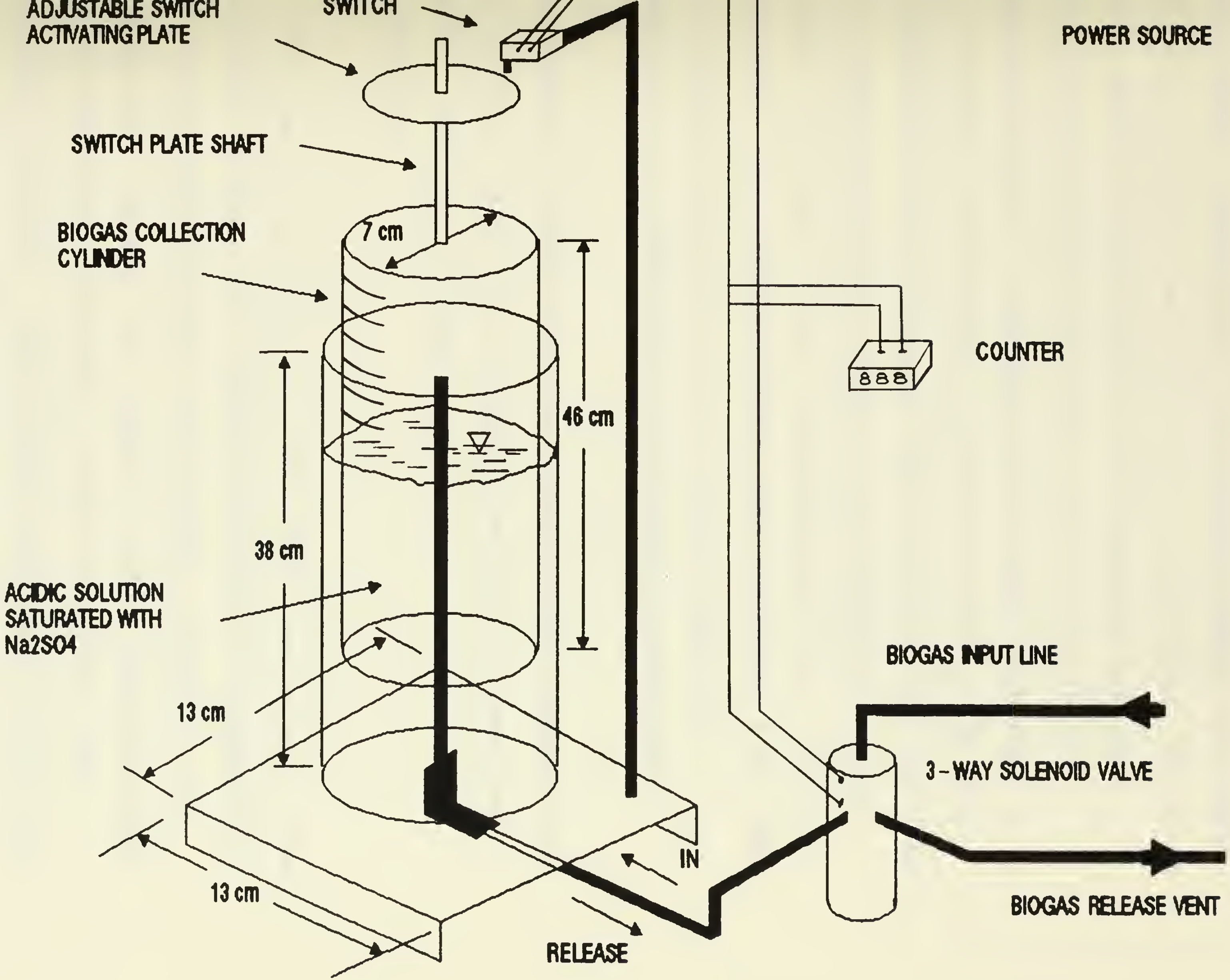
then analyzed by capillary column gas chromatography-mass spectrometry (GC-MS) using an internal standard. For the volatile organic compounds, the purge-and-trap technique was used in combination with GC-MS analysis.

Gas composition was determined using two instruments. Methane, CO_2, O_2, and N_2 percentages were evaluated periodically using a Fischer gas partitioner (Model 25V) fitted with a molecular sieve (13X) column in series with a DEHS column and operated at room temperature. Gaseous hydrogen analyses were performed using a Perkin-Elmer (Model 900) gas chromatograph fitted with a thermal conductivity detector and molecular sieve (5 Å), which was also operated at room temperature.

Volumetric gas production was measured continuously by volumetric displacement over time. Plexiglass meters of the type illustrated in Figure 7 were calibrated individually and meter readings recorded daily. All raw gas production data were converted to volumes at standard temperature and pressure (0° Celcius and 760 mm Hg) using the ideal gas law to facilitate data comparison.

<u>Sampling Procedures</u>

Leachate samples collected for trace organic analysis were handled in accordance with procedures outlined in EPA


ADJUSTABLE SWITCH
ACTIVATING PLATE
SWITCH
POWER SOURCE
SWITCH PLATE SHAFT
BIOGAS COLLECTION
CYLINDER
7 cm
46 cm
COUNTER
888
38 cm
ACIDIC SOLUTION
SATURATED WITH
Na2SO4
BIOGAS INPUT LINE
13 cm
3 - WAY SOLENOID VALVE
IN
13 cm
BIOGAS RELEASE VENT
RELEASE

600/4-79-019, Section 8.2. Thoroughly rinsed, oven-baked glass bottles were used with teflon-lined lids. The 40-mL vials used to collect samples for purgeable organics analysis were filled completely, with no air space. Samples collected for metals analysis were contained in acid-washed, screw-capped polyethylene bottles and were preserved by the addition of nitric acid to a pH less than 2. All remaining leachate samples were collected in acid-washed, thoroughly-rinsed polyethylene bottles. After collection, all leachate samples were stored at 4 ^{o}C, and all analyses commenced within 24 hours except pH, alkalinity, and ORP which were performed immediately.

Gas samples withdrawn from the lysimeter head spaces were collected in air-tight syringes from built-in sampling ports. Analyses of these samples were performed immediately.

As the samples collected were delivered immediately to the analysts' custody in an adjacent building, no documented chain-of-custody procedure was utilized. However, all samples were logged into a sample log book which included details regarding the sampler, type of analysis, and recipient personnel. Concise and clear sample labels were essential, and had the following form:

Figure 8 Typical Sample Label

Column No:_______ Date:____/____/____

Master Log Number:________________________________

Analysis:_________________ Sample Volume:_______

Preservative Amount:__________ Type:____________

Sampled by:_______________________________________

Observations:_____________________________________

Chapter IV: Results and Discussion

Lysimeter Operation

The first day after the simulated landfill columns were loaded (i.e., project Day 1), tap water additions to all ten columns commenced in order to quickly bring the test cells to field capacity. Water additions of 12 liters per day were made over the first 34 project days leading to the attainment of field capacity on or about Day 35. In order to ensure sufficient leachate production to facilitate sampling and recycle throughout the experimental period, water additions continued to all ten columns, but at the reduced rate of 6 liters per day, through Day 46. After Day 46, moisture was introduced to all ten columns through the application of 6 liters of tap water on Days 68, 75, 78 and 82; and the addition of 6 liters of a "seeding" mixture on 23 occasions between Days 666 and 898. This seeding was performed to expedite establishment of a viable flora of methanogenic bacteria, and is discussed in detail subsequently. Thereafter, routine moisture additions were made only to the single pass columns as the leachate management strategies were implemented.

Approximately 130 days after loading, the two leachate management strategies, leachate recirculation and single

pass leaching, were initiated in the respective simulated landfill cells. In the recycle cells, 1 (CR), 6 (OR), 7 (OLR), 9 (OMR) and 10 (OHR); leachate was pumped, in one dose every three days, to the top of the columns and allowed to pass through the refuse mass. The volumes of recycled leachate were unmeasured during this initial operational period which continued until Day 663, and corresponded with the acid formation phase of landfill stabilization within the simulator columns. (Appendix I tabulates leachate volumes recycled throughout the experimental period.)

Single pass leaching in cells 2 (CS), 3 (OS), 4 (OLS), 5 (OMS) and 8 (OHS), was simulated through the combined effect of water additions and the scheduled discard of leachate. Beginning on Day 103, and continuing through Day 462, 6 liters of water were routinely applied, in one dose, every three days, to the single pass columns. From Day 474, the frequency of this water addition was lessened to once every 9 days, the schedule followed for the remainder of the experimental period. Initially, the total accumulated leachate was discarded approximately every 3 days. On Day 482, however, the discarded quantity was decreased to 1.8 liters every three days so that leachate could accumulate, thereby providing abundant soluble substrate for the methane fermenting bacteria that were

introduced during the seeding procedure that followed.

Prior to Day 666, the simulated landfill cells were intentionally operated so as to maintain the acid formation phase of stabilization as indicated by depressed leachate pH (Figures 9 and 10), and elevated chemical oxygen demand (COD) (Figures 11 and 12) and total volatile acids (TVA) (Figures 13 and 14) concentrations. This condition was maintained so that the effects of the pollutant loadings could be observed during a period when the mobility of the pollutants, especially the heavy metals, was most enhanced. Since soil was not placed in the landfill simulators, it was necessary to artificially provide a methane producing microbial "seed" to the refuse to facilitate establishment of the methane fermentation phase of stabilization in a reasonable period of time. To overcome the inhibition due to the high volatile acid concentrations, pH adjustments were included in this seeding process. (Appendix II provides a tabular summary of the seeding process.)

Anaerobic digester effluent from the R. M. Clayton wastewater treatment plant, Atlanta, GA, was used as the source of methanogenic bacteria (i.e., "seed") for the ten experimental cells. The digester sludge had a pH of 7.9, alkalinity of 3.1 grams per liter (as $CaCO_3$) and a total solids concentration of 2.5 % with a volatility of 60 %.

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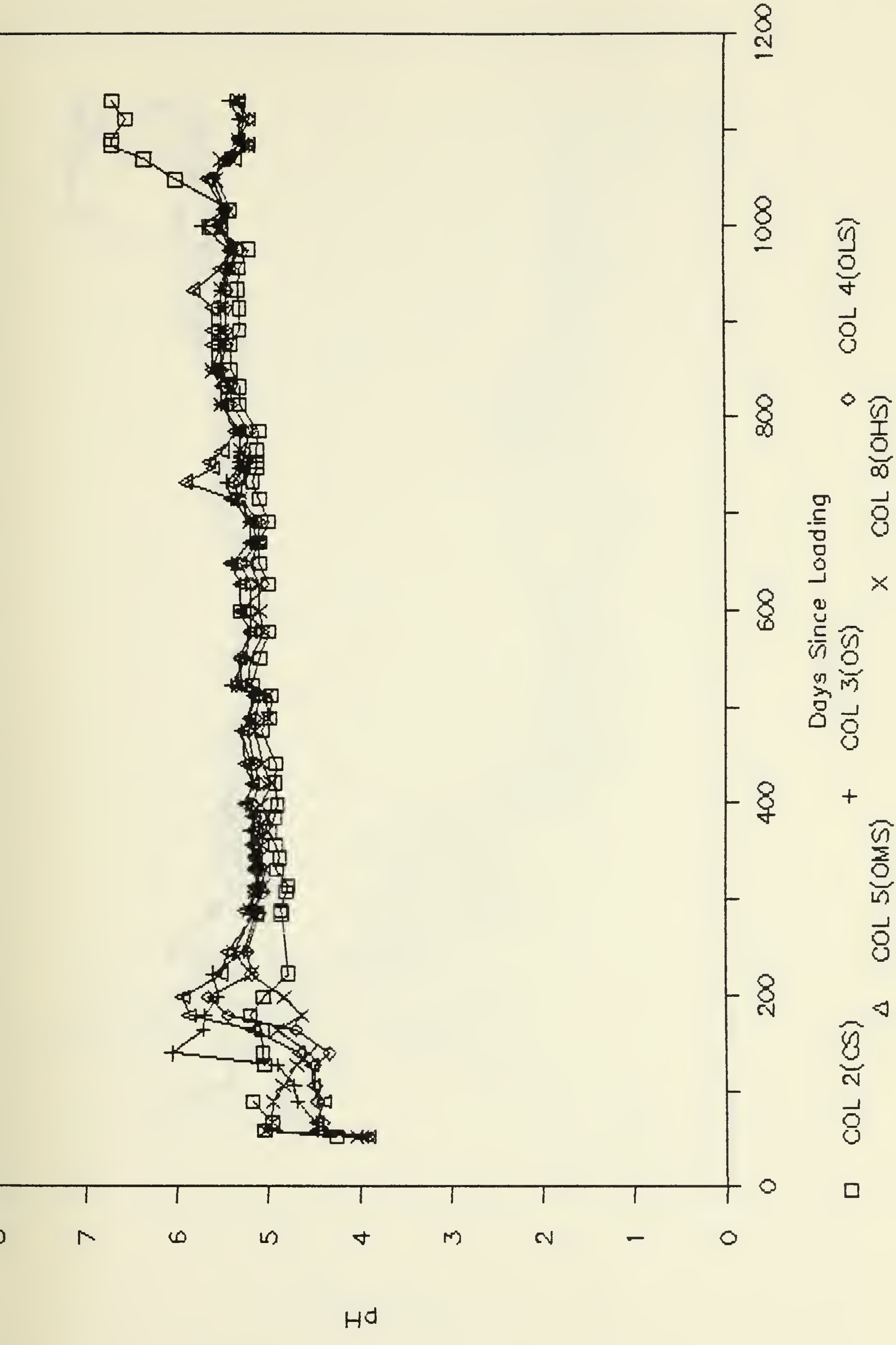
[illegible]

[illegible]

[illegible]


pH
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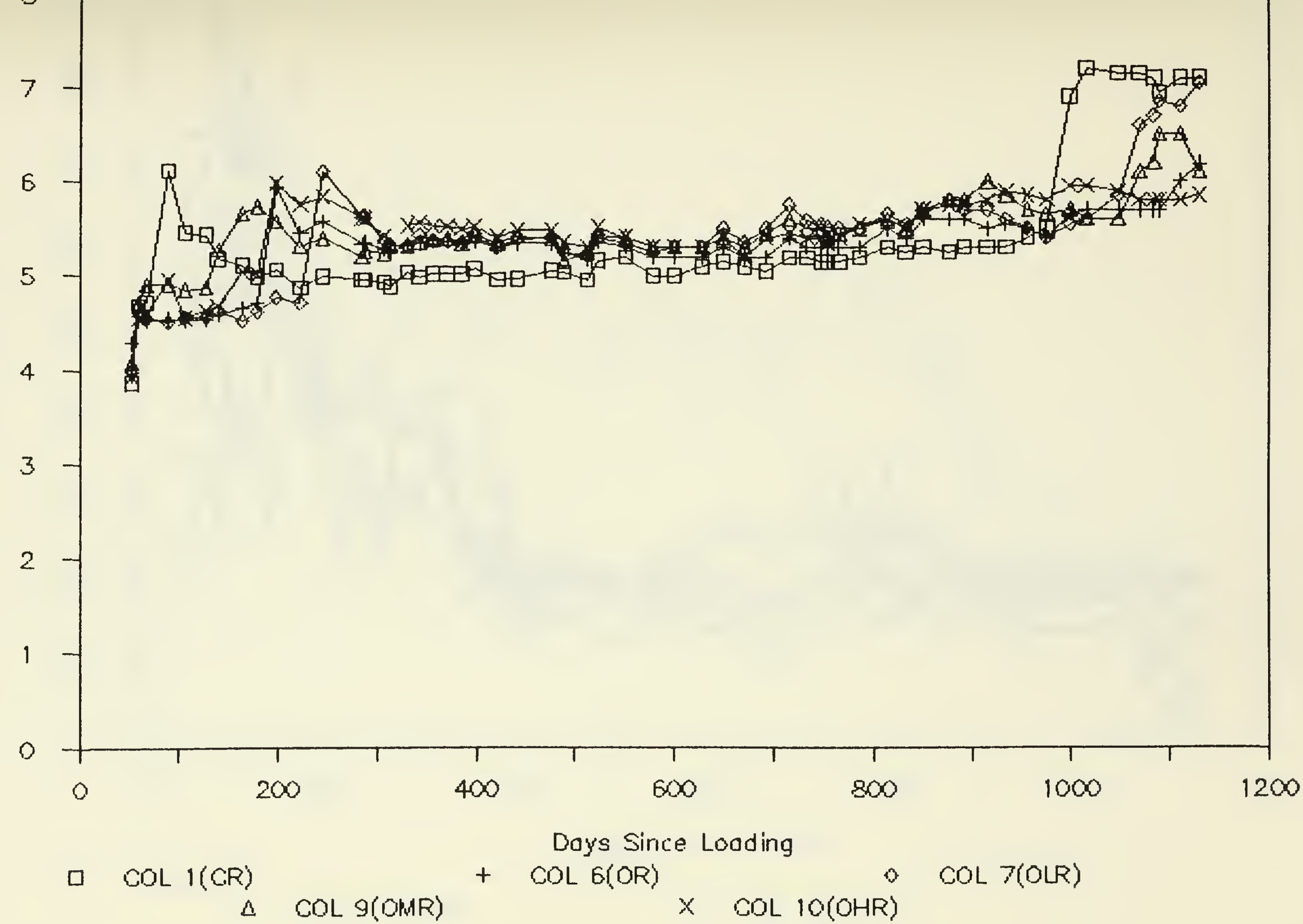
1
2
3
4
5
6
7
0
200
400
600
800
1000
1200
Days Since Loading
COL 2(CS)
COL 3(OS)
COL 4(OLS)
COL 5(OMS)
COL 8(OHS)


pH
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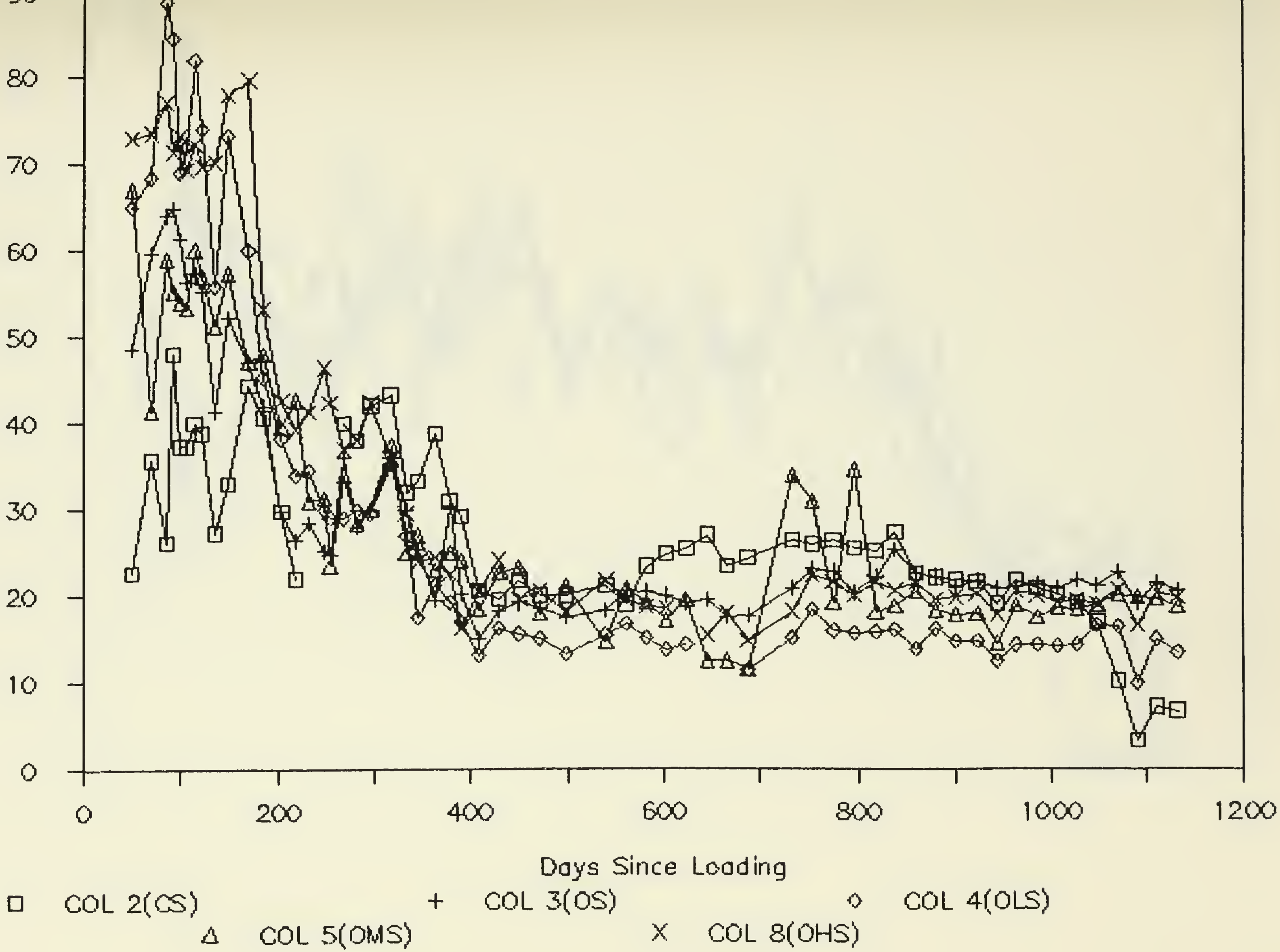
1
2
3
4
5
6
7
0
200
400
600
800
1000
1200
Days Since Loading
COL 1(CR)
COL 6(OR)
COL 7(OLR)
COL 9(OMR)
COL 10(OHR)


COD (mg/L)
(Thousands)
0
10
20
30
40
50
60
70
80
0
200
400
600
800
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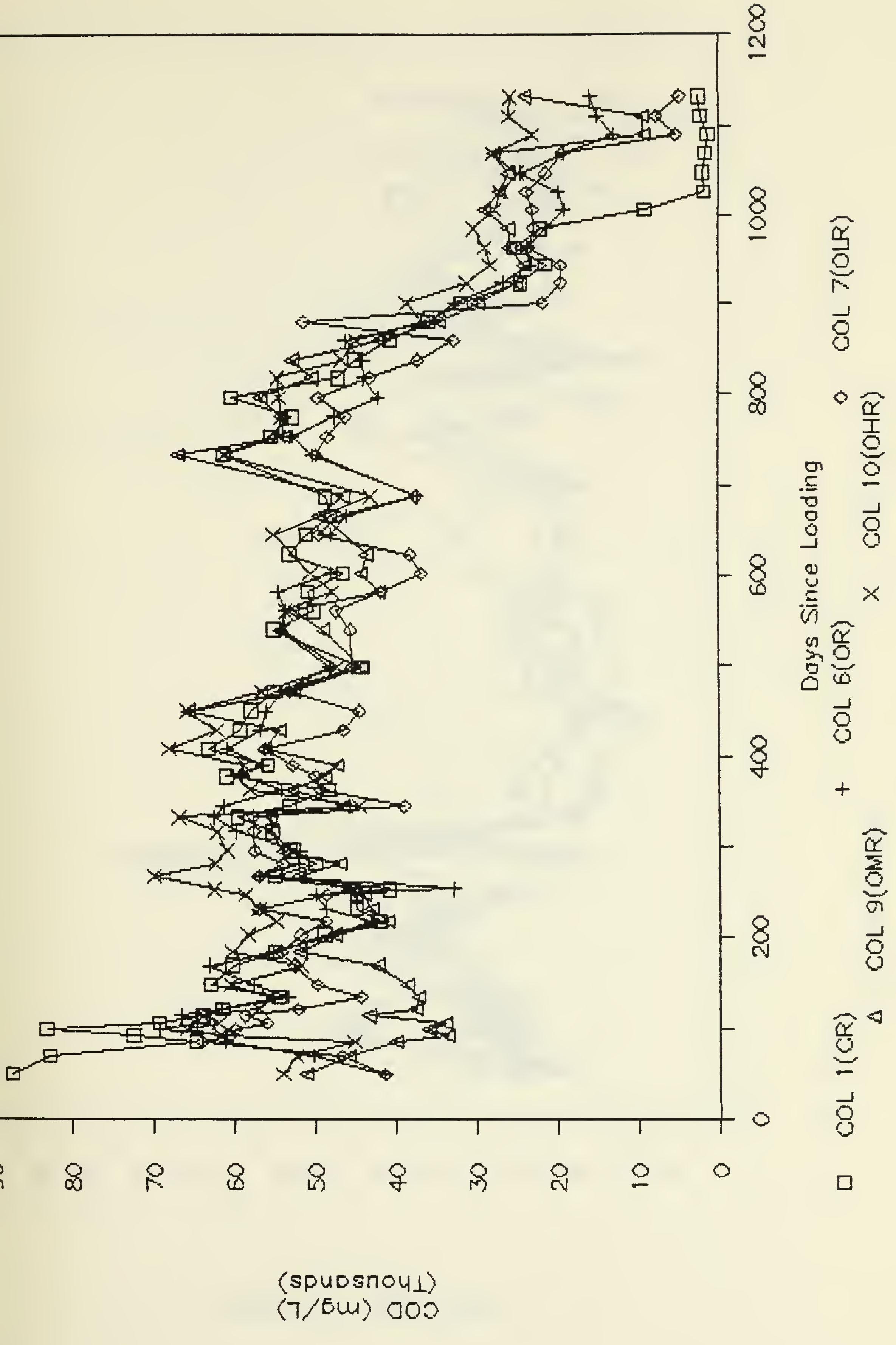
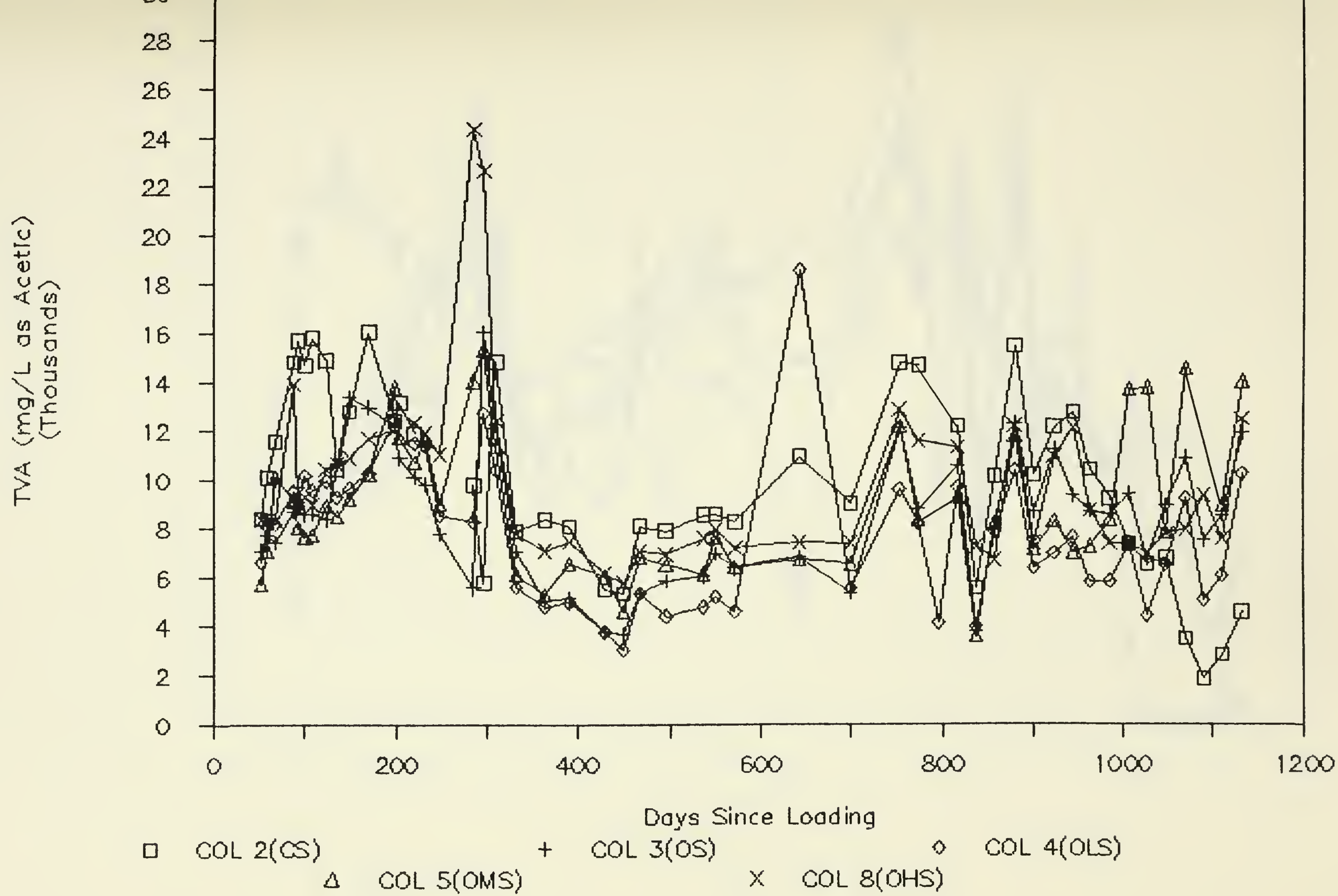
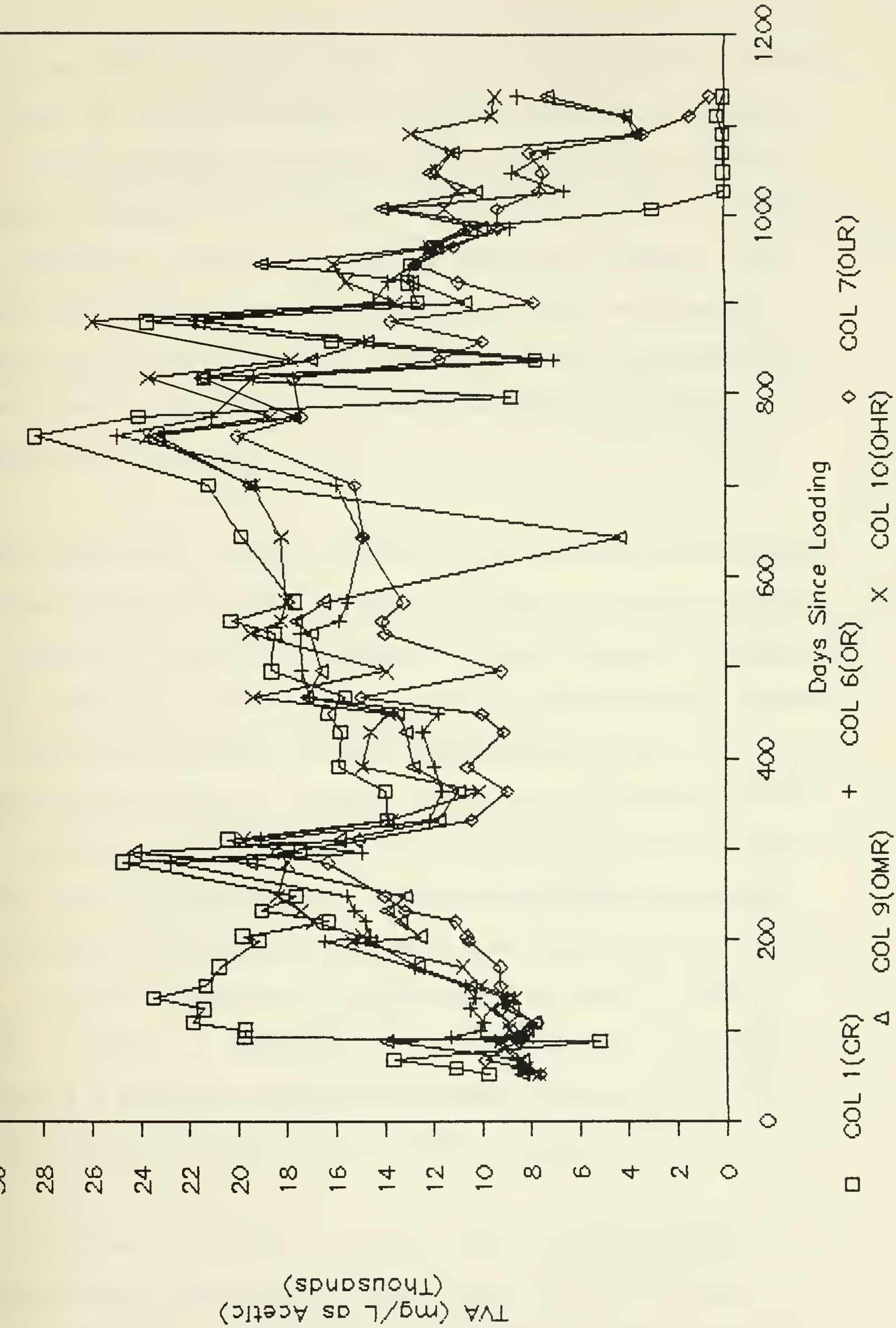
Days Since Loading
COL 2(CS)
COL 3(OS)
COL 4(OLS)
COL 5(OMS)
COL 8(OHS)


COD (mg/L)
(Thousands)
Days Since Loading
COL 1(CR)
COL 9(OMR)
COL 6(OR)
COL 10(OHR)
COL 7(OLR)


TVA (mg/L as Acetic)
(Thousands)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
0
200
400
600
800
1000
1200
Days Since Loading
COL 2(CS)
COL 3(OS)
COL 4(OLS)
COL 5(OMS)
COL 8(OHS)

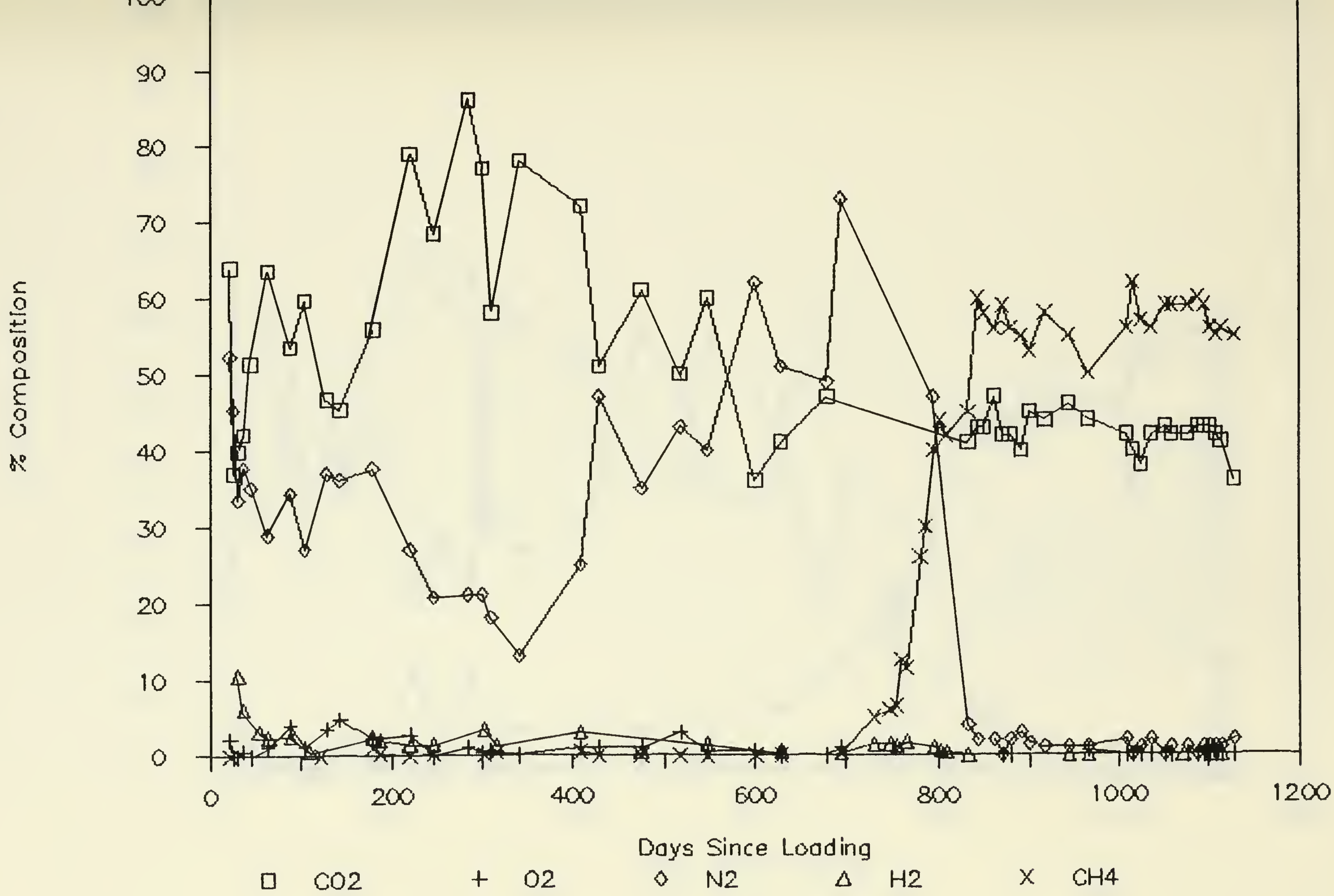


TVA (mg/L as Acetic)
(Thousands)
Days Since Loading
□ COL 1(CR)
+ COL 6(OR)
◇ COL 7(OLR)
△ COL 9(OMR)
X COL 10(OHR)

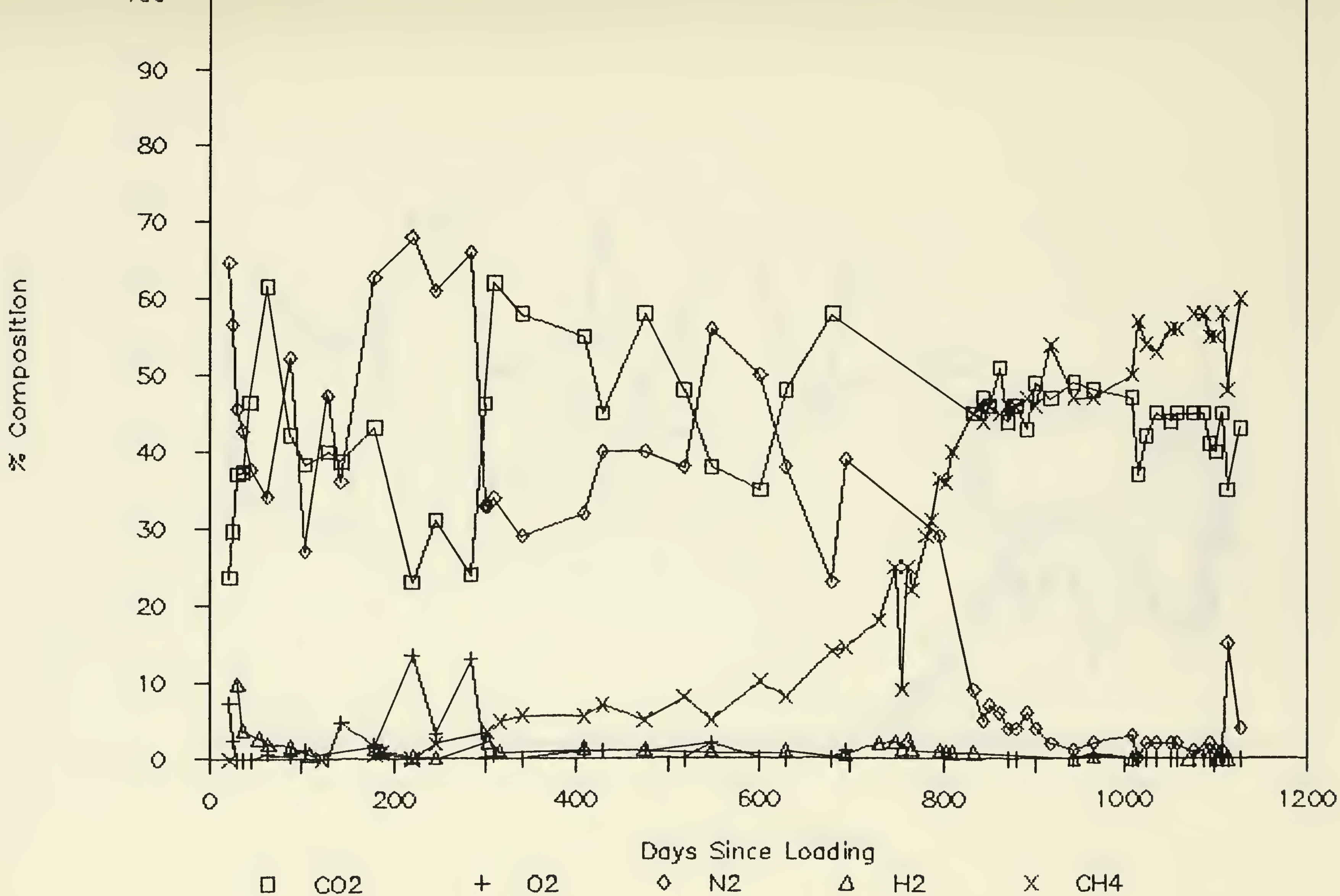
From Day 666 to Day 770 eight seedings were made to the ten columns by the application, in each instance, of 5 liters of digester sludge followed by 1 liter of water (added to prevent fouling in the liquid distribution pipe). As noted in Appendix I, between 2 and 4.5 liters of leachate were recycled in the columns incorporating that management strategy immediately prior to five of these seedings with the intent of providing the methanogens with readily available substrate.

Before Day 666, the date of the first seeding, the highest methane concentrations observed in each of the test cells, as shown in Figures 15 through 24, and indicated in Appendix III, was 1 % in the recycle columns, except Column 9 (OMR) in which methane had not yet been detected, and 10 % in the single pass control, Column 2 (CS); 2 % in Column 8 (OHS), but undetected in the remaining single pass cells. During this first seeding period, methane concentrations slowly increased with maximum concentrations reaching 13 %, 4 %, 5 %, 3 % and 4 % methane in the recycle columns 1 (CR), 6 (OR), 7 (OLR), 9 (OMR) and 10 (OHR); and 25 %, 7 %, 3 %, 4 % and 3 % methane in the single pass columns 2 (CS), 3 (OS), 4 (OLS), 5 (OMS) and 8 (OHS), respectively.

The slow pace at which a viable flora of methanogenic bacteria was developing was believed to be the result of acid inhibition. Leachate recirculated in the recycle



% Composition
0
10
20
30
40
50
60
70
80
90
0
200
400
600
800
1000
1200
Days Since Loading
□ CO2
+ O2
◇ N2
Δ H2
X CH4


90
80
70
60
50
40
30
20
10
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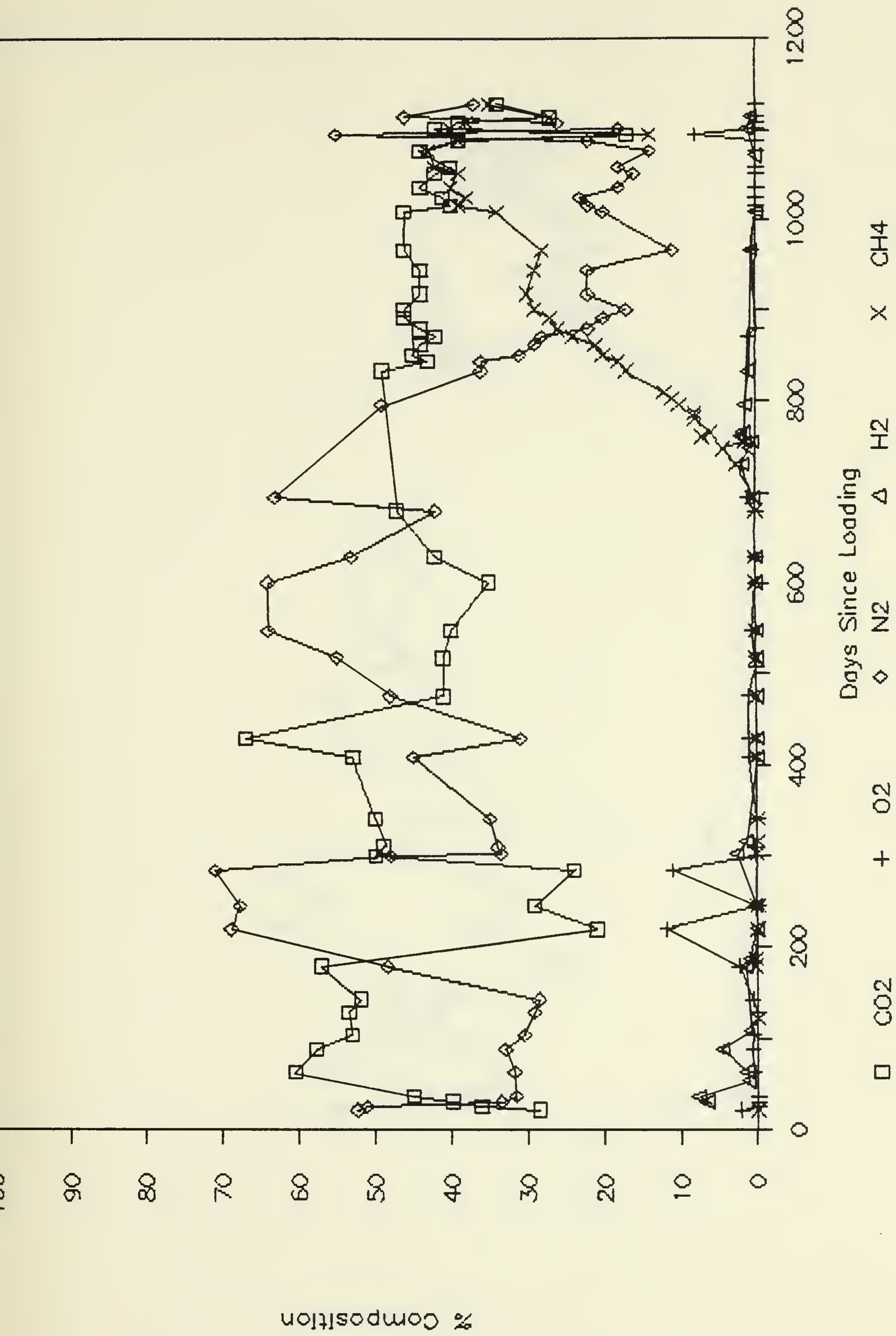
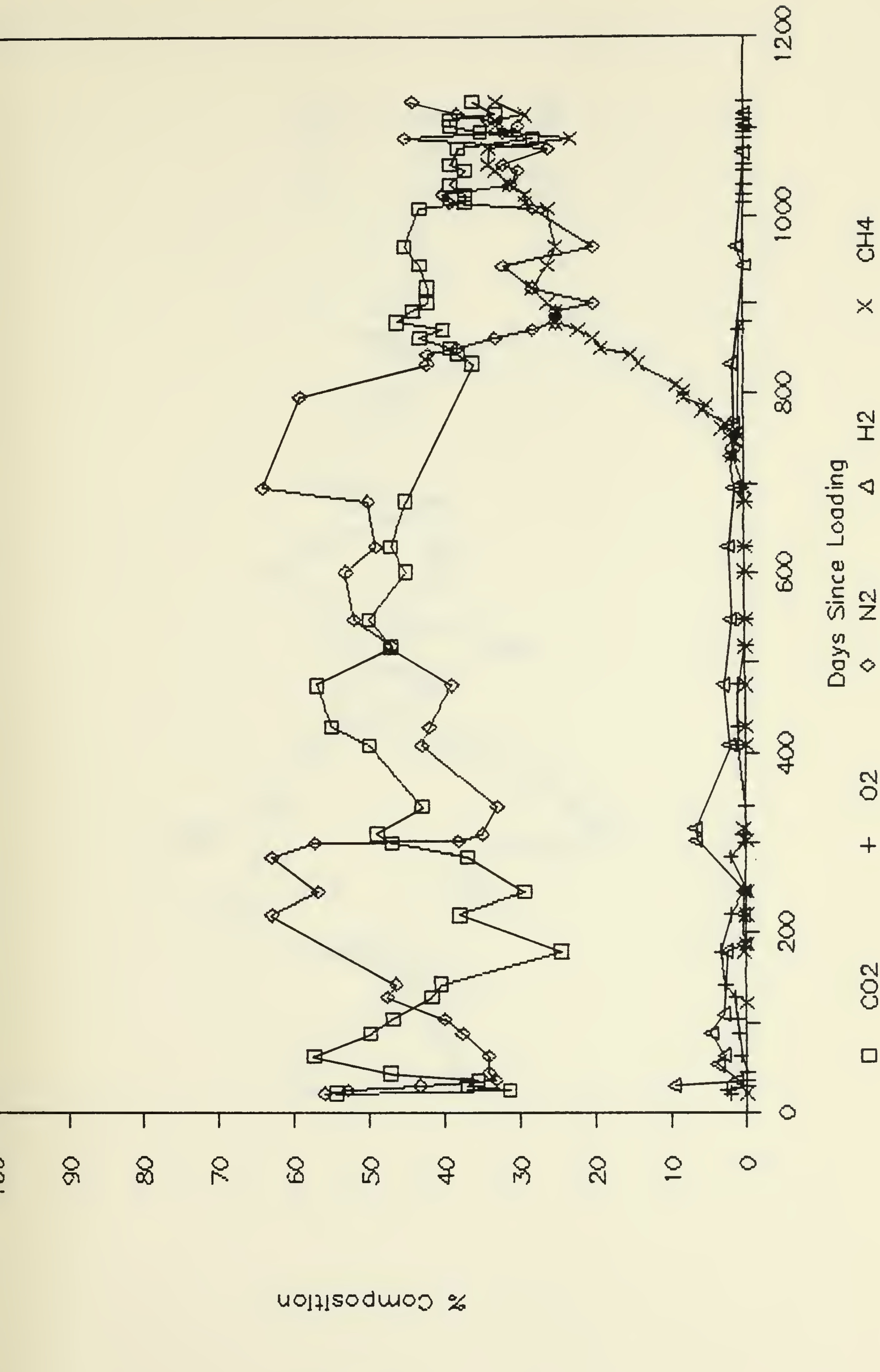
% Composition
0
200
400
600
800
1000
1200
Days Since Loading
CO2
O2
N2
H2
CH4


% Composition
90
80
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
Days Since Loading
□ CO2 + O2 ◇ N2 Δ H2 X CH4



% Composition
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200
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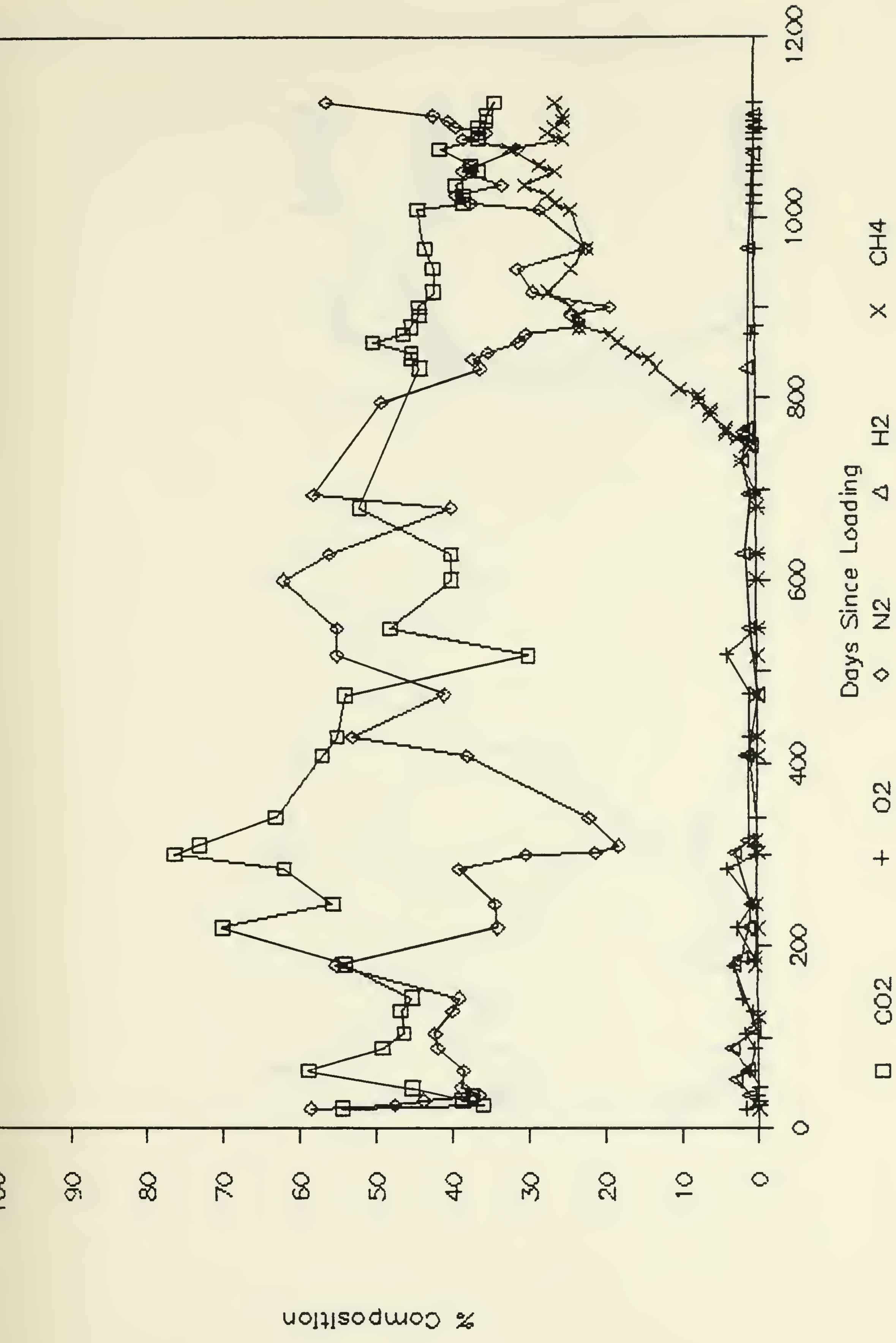
1200
Days Since Loading
□ CO2 + O2 ◇ N2 Δ H2 X CH4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Days Since Loading
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1200
0
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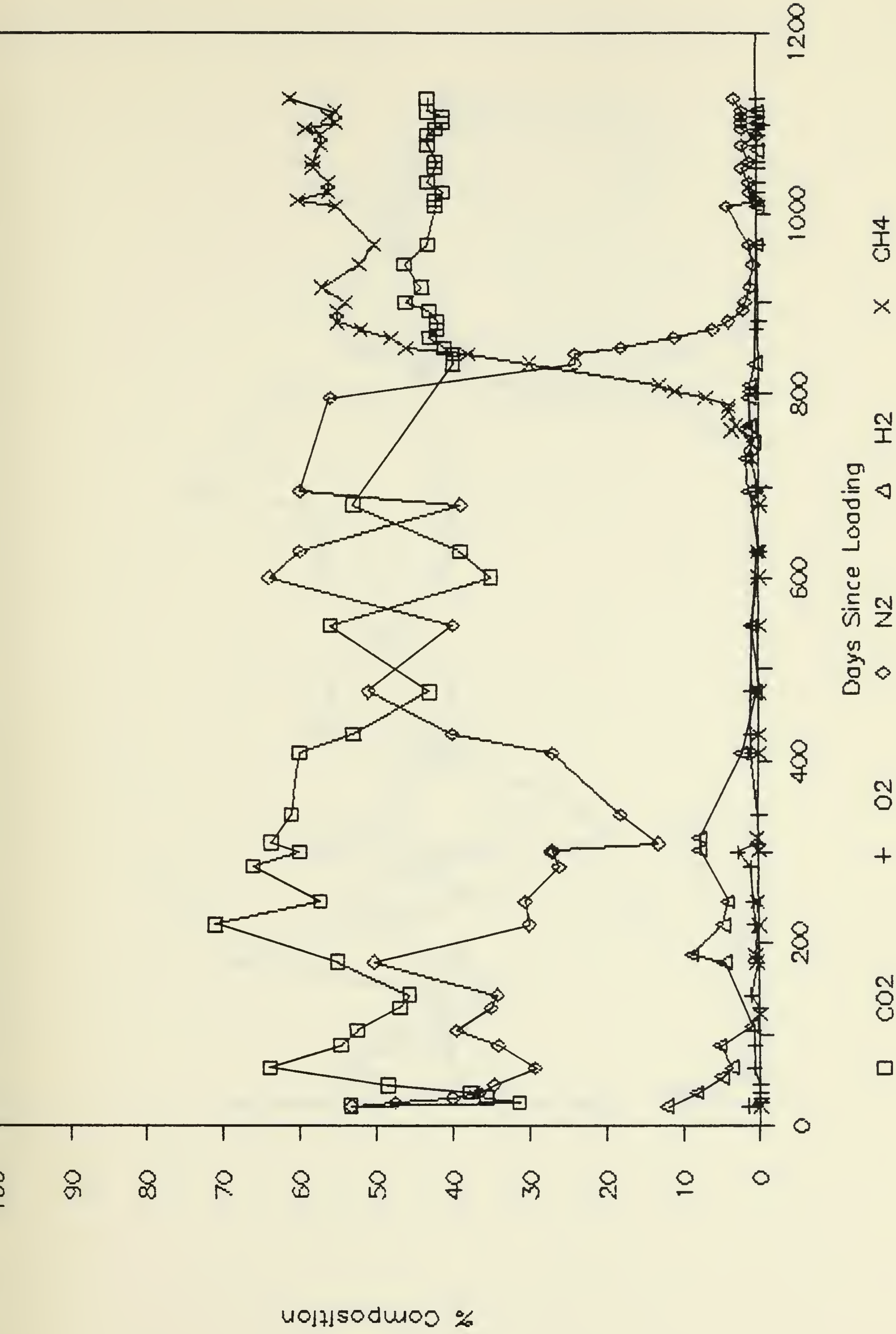
□ CO2
+ O2
◇ N2
Δ H2
X CH4



% Composition
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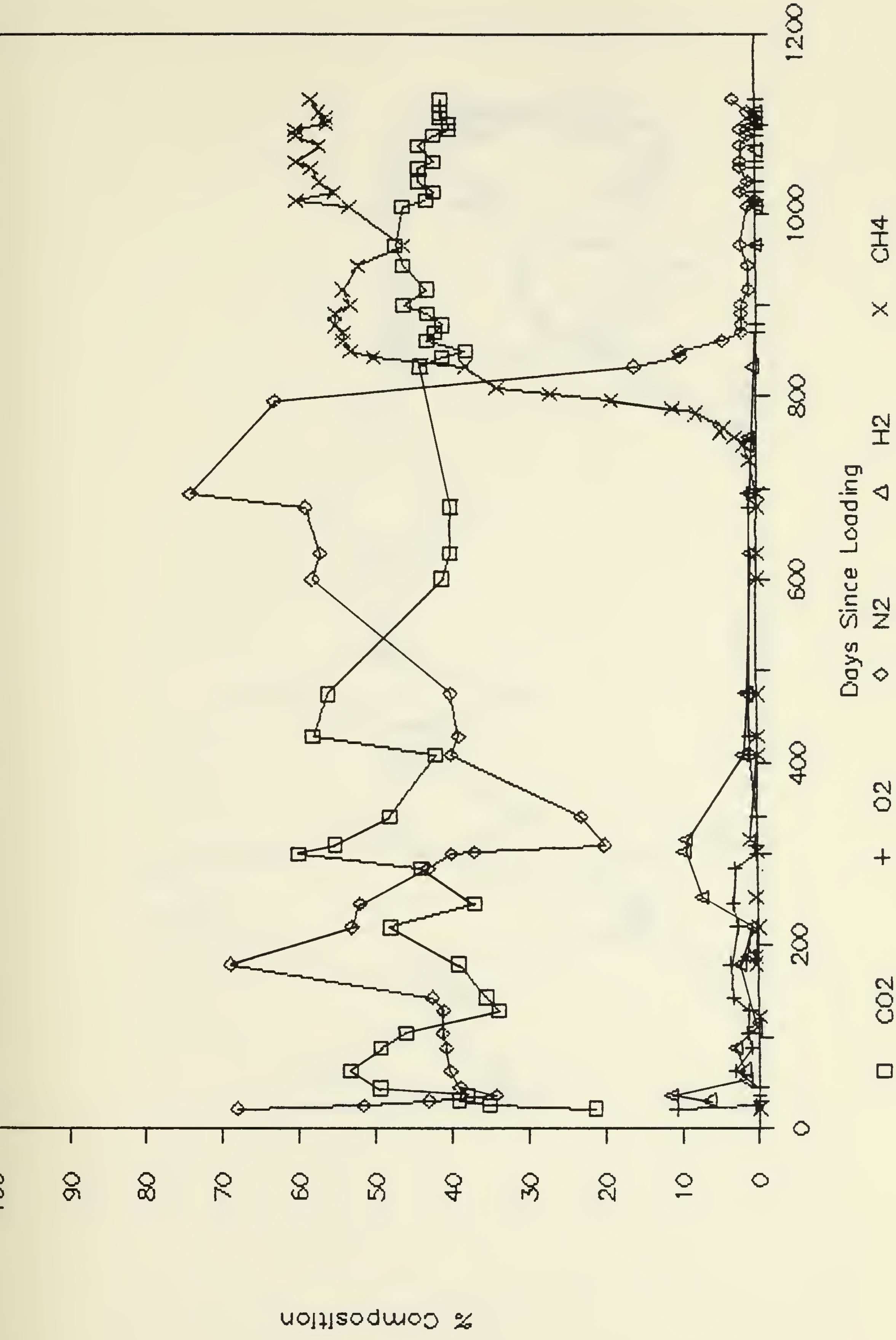
Days Since Loading
□ CO2 + O2 ◇ N2 Δ H2 X CH4



% Composition
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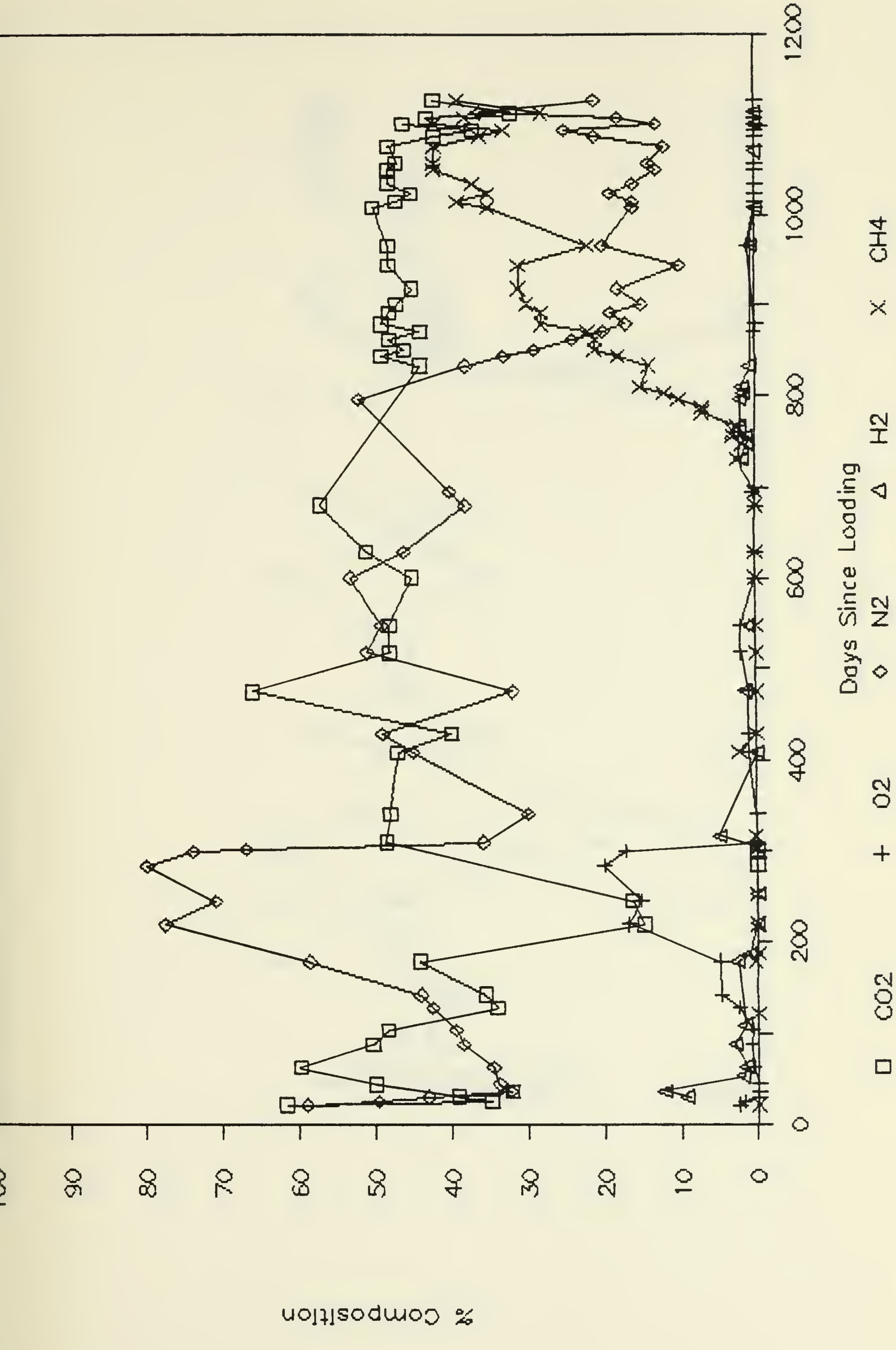
1000
1200
Days Since Loading
□ CO2 + O2 ◇ N2 Δ H2 X CH4


% Composition
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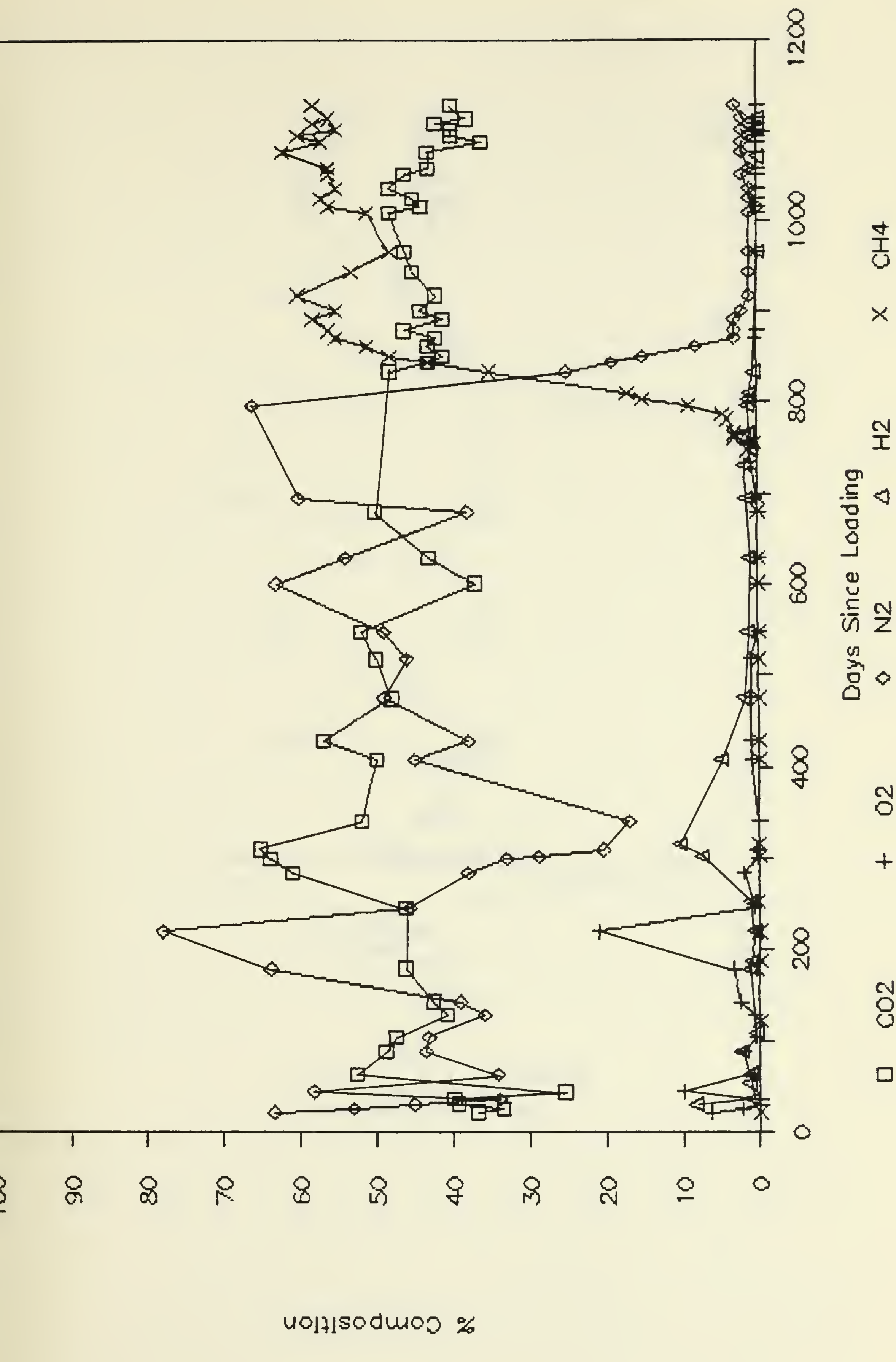
Days Since Loading
□ CO2 + O2 ◇ N2 Δ H2 X CH4


% Composition
0
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20
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40
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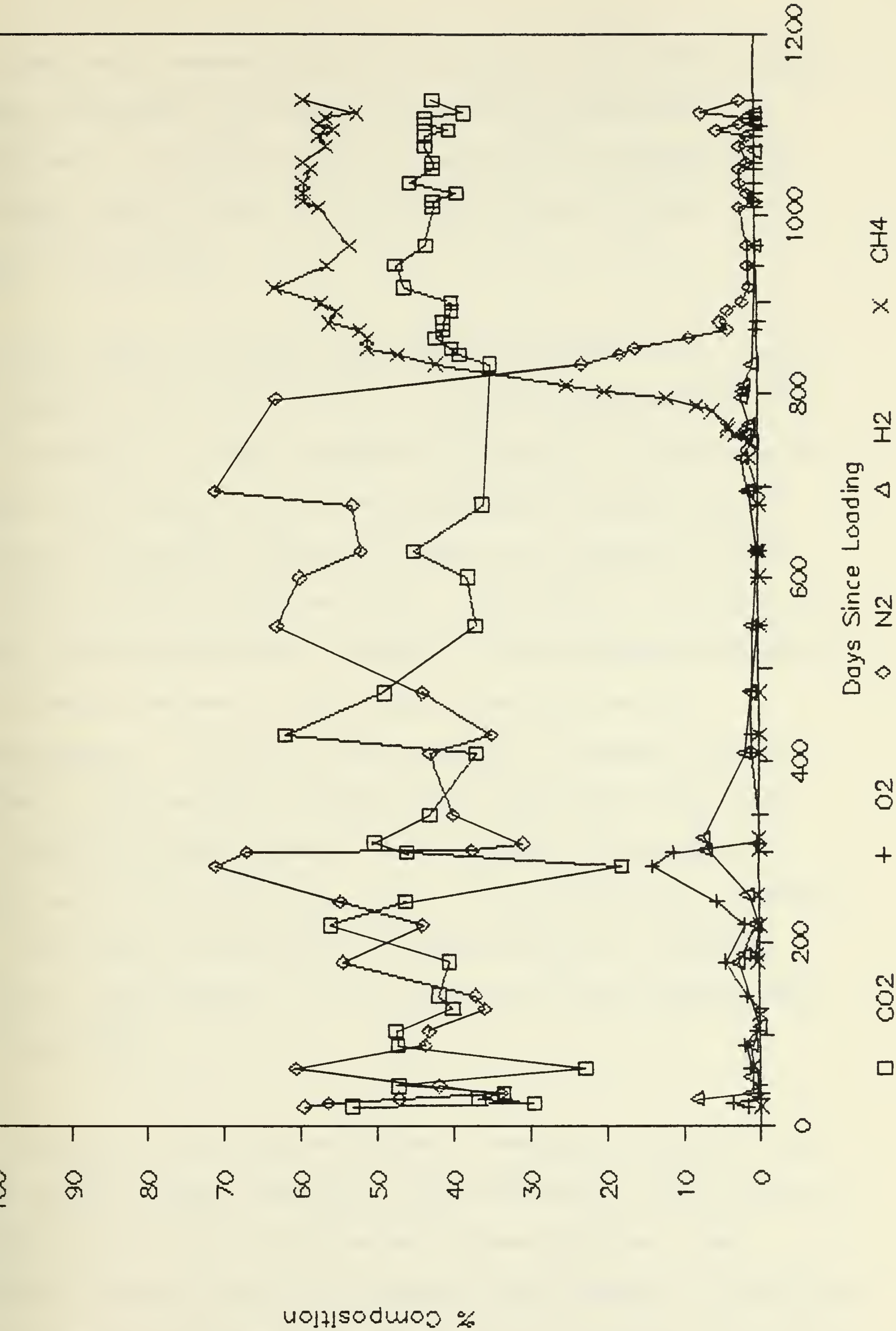
1000
1200
Days Since Loading
□ CO2 + O2 ◇ N2 Δ H2 X CH4


% Composition
100
90
80
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
Days Since Loading
□ CO2 + O2 ◇ N2 Δ H2 × CH4

columns had a measured pH in the 5.05 to 5.75 range and was likely adversely affecting the applied methanogens. Therefore, a revised protocol was used for seedings nine through twenty which were performed between project Days 775 and 877.

The new seeding procedure included the removal of 1 liter of leachate from each column, the addition of Na_2CO_3 (150 g/L solution) to that leachate to raise its pH into the 6-7 range, the mixing of the pH-neutralized leachate with 4 liters of anaerobic digester sludge and addition of that mixture to the respective cells. As before, 1 liter of water was applied after the seed. This procedure enhanced the contact between a less harsh substrate and the methanogens. In view of this protocol, leachate was, in effect, also recycled through the single pass test cells during this seeding phase. As an additional measure to alleviate acid inhibition, prior to recirculation, leachate in the recycle columns was pH-neutralized in a similar manner, using Na_2CO_3, on 23 consecutive days (between Days 782 and 825).

By the end of this second phase of seeding on Day 877, all the columns showed significant improvements in gas quality. Figures 15 through 24 illustrate these changes. The control columns showed the greatest improvement, as would be anticipated, considering the potential inhibitory effects of

the loaded priority pollutants. Methane concentrations as high as 59 % and 46 % were measured during this period in columns 1 (CR) and 2 (CS), respectively. Detected levels of methane in the other recycle columns: 6 (OR), 7 (OLR), 9 (OMR) and 10 (OHR) rose to 55 %, 55 %, 56 % and 56 %, respectively. Lagging the correspondingly loaded recycle columns, single pass columns 3 (OS), 4 (OLS), 5 (OMS) and 8 (OHS) showed gas quality improvements with methane detected at 26 %, 25 %, 23 % and 28 %, respectively. This slower improvement in gas quality observed in the single pass columns illustrates the acceleration effect that leachate recirculation has on the microbially-mediated stabilization process.

Since a viable population of methane fermenting bacteria seemed well established within the test cells, the last three scheduled seedings on Days 884, 891 and 898 reverted back to the original addition of 5 liters of digester sludge followed by 1 liter of water. These seedings were made to help acclimate the microbial population to the natural environmental conditions within the test cells.

With methane fermentation ongoing, operation of the simulated landfill columns was then oriented towards adherence to fixed schedules to allow clearer assessments of the two leachate management strategies during this very

[illegible]

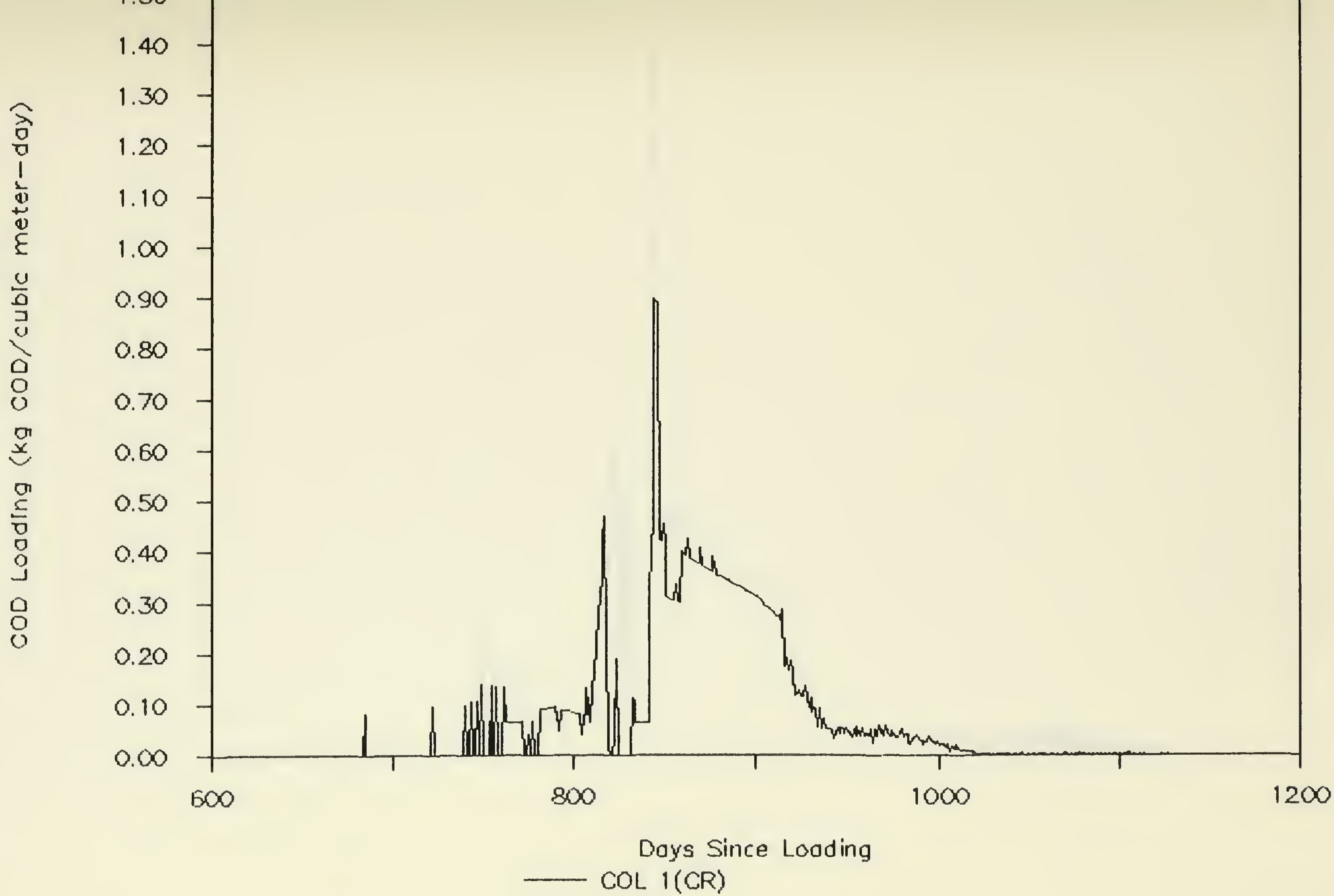
active phase of biological stabilization. After the last seeding, on Day 898, single pass leaching was simulated by the continued water additions of 6 liters every nine days and leachate discard of 1.8 liters every three days. On Day 973 the total accumulated leachate was discarded from the single pass cells, yielding volumes of 36, 24, 27, 45 and 33 liters from Columns 2 (CS), 3 (OS), 4 (OLS), 5 (OMS) and 8 (OHS), respectively. Thereafter, the total accumulated leachate was similarly discarded every three days in order to accelerate the effects of washout. It was observed that over subsequent nine-day periods, the leachate drained generally balanced the 6 liters of water added, although the drainage often occurred in a somewhat random and differential pattern.

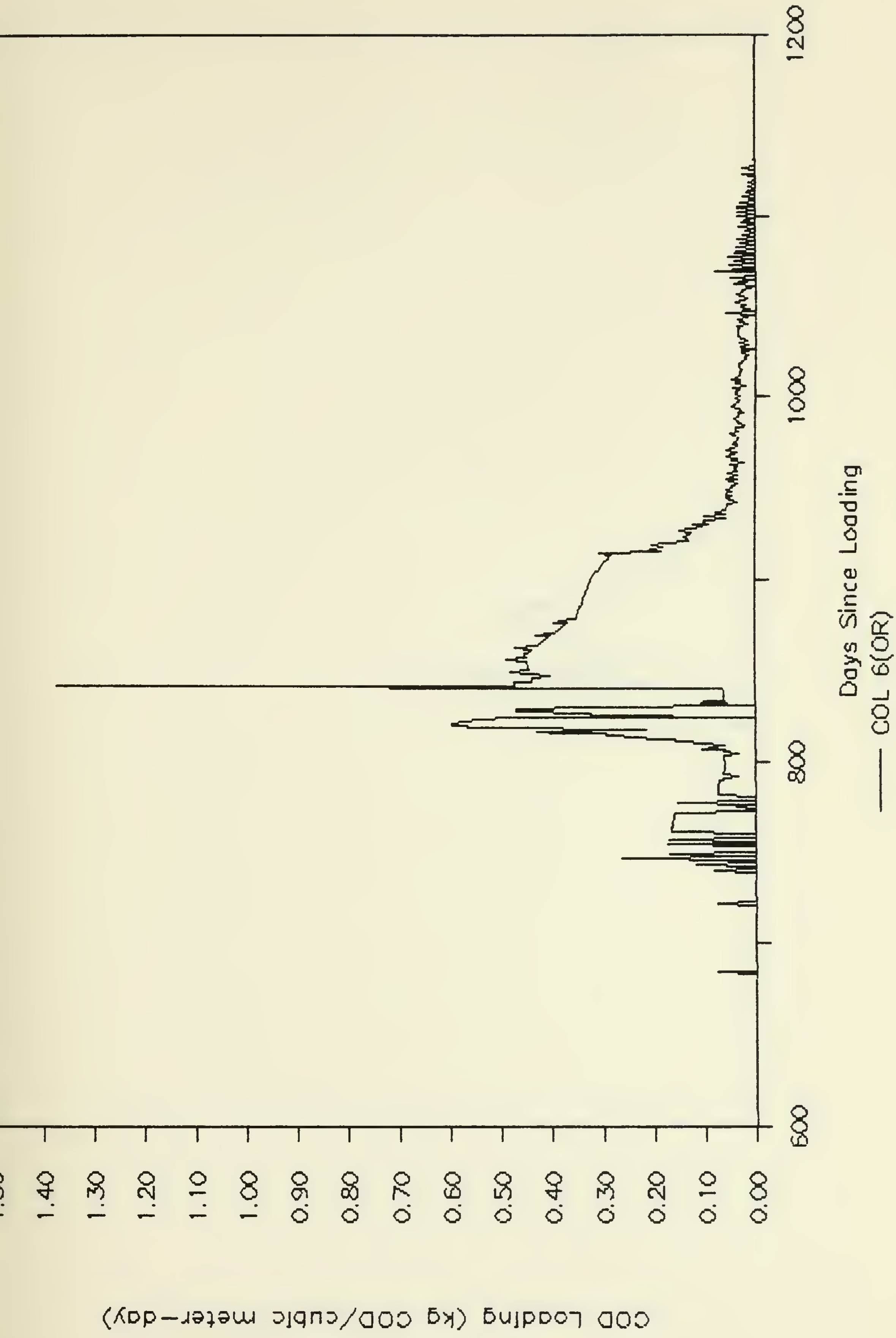
Beginning on Day 782, leachate recycle was performed in columns 1 (CR), 6 (OR), 7 (OLR), 9 (OMR) and 10 (OHR) on a daily basis. Due to mechanical difficulties, between Days 782 and 858, the volumes of leachate recycled varied both day to day and between columns, as indicated in Appendix I. However, on Day 858, three days after the seventeenth seeding, a recycle schedule of 12 liters per day was initiated and followed until Day 916 when the accumulated leachate in Column 6 (OR) was only 8 liters. From that day forward, the quantity of leachate available for recycle in Column 6 (OR) gradually decreased. Therefore, in order to maintain a constant daily recycle volume through each of

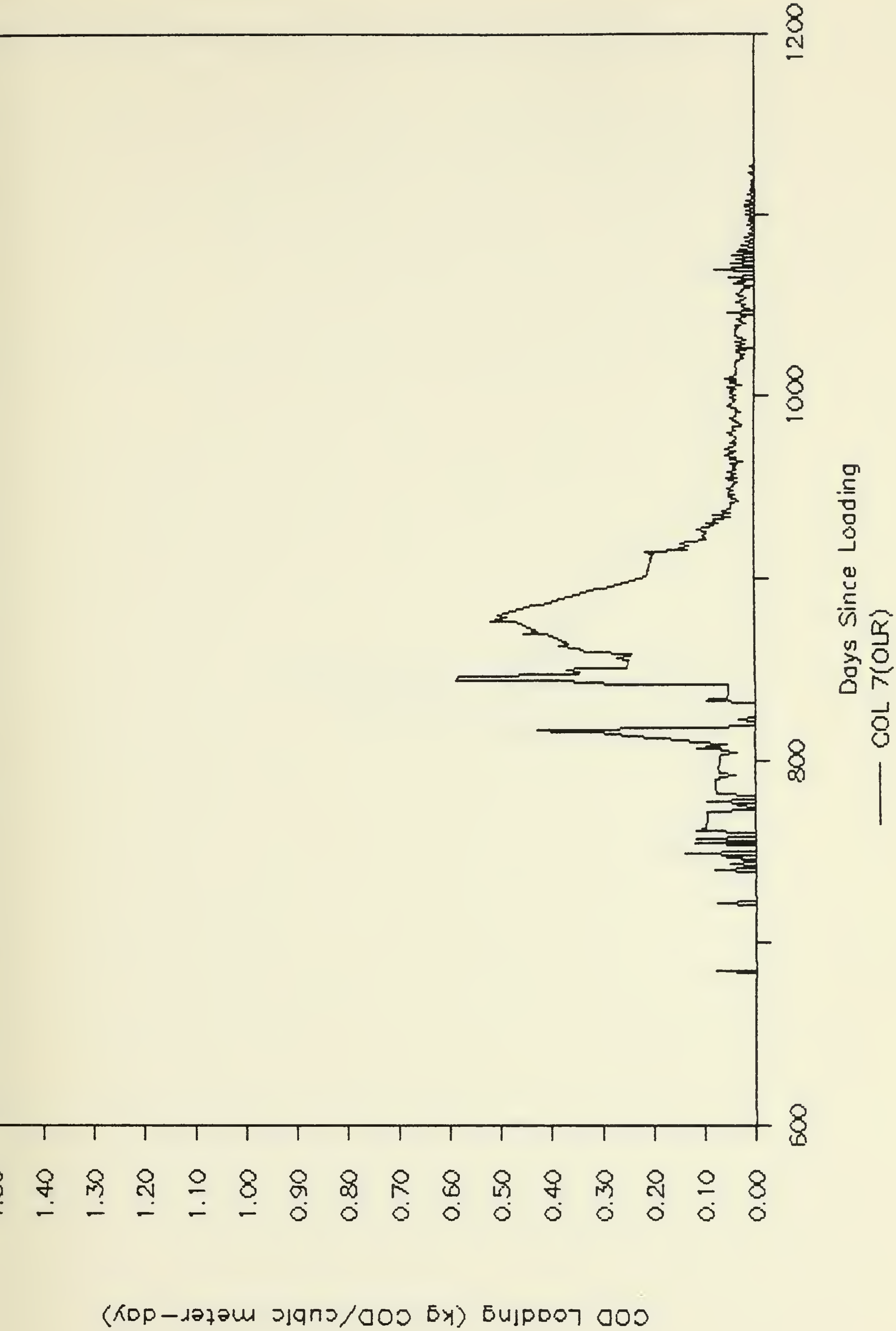
the five recycle columns, the amount of leachate produced by Column 6 (OR) was the amount recycled through all five recycle columns. This decrease in leachate production from Column 6 (OR) was considered the result of increased microbial activity and biomass growth, as well as a more complete saturation of the waste mass and possible retention of leachate in the void spaces.

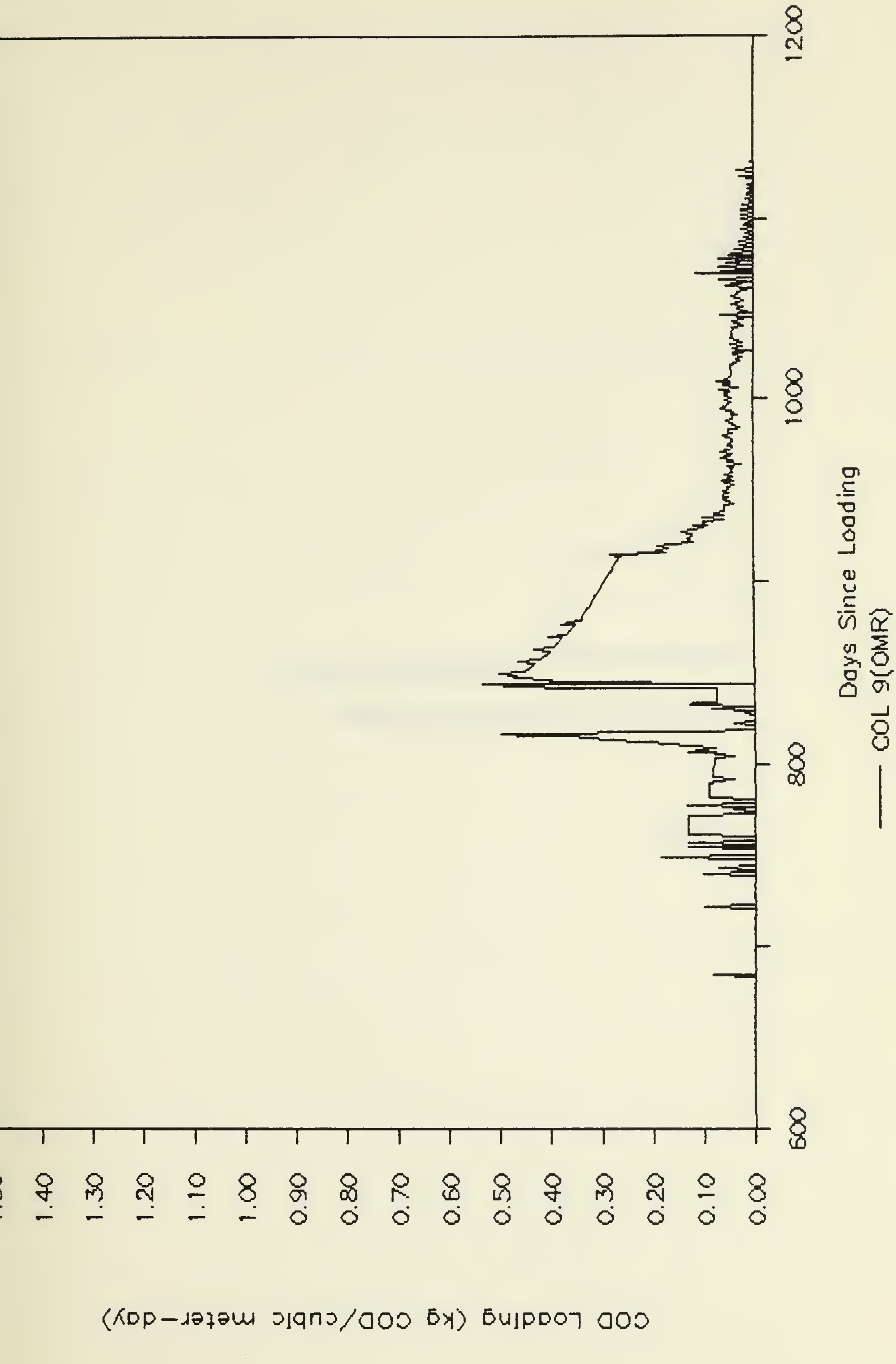
Daily leachate production from Columns 6 (OR) continued to decrease. Falling to below 2 liters per day prompted a change in recycle schedule from daily recycle to recycle every other day, beginning on Day 1063. However, leachate production from Columns 6 (OR) continued to decline and upon reaching only 1 liter in two days, the recycle schedule was again changed, to once every fourth day, the schedule followed from Day 1119 through the remainder of the experimental period.

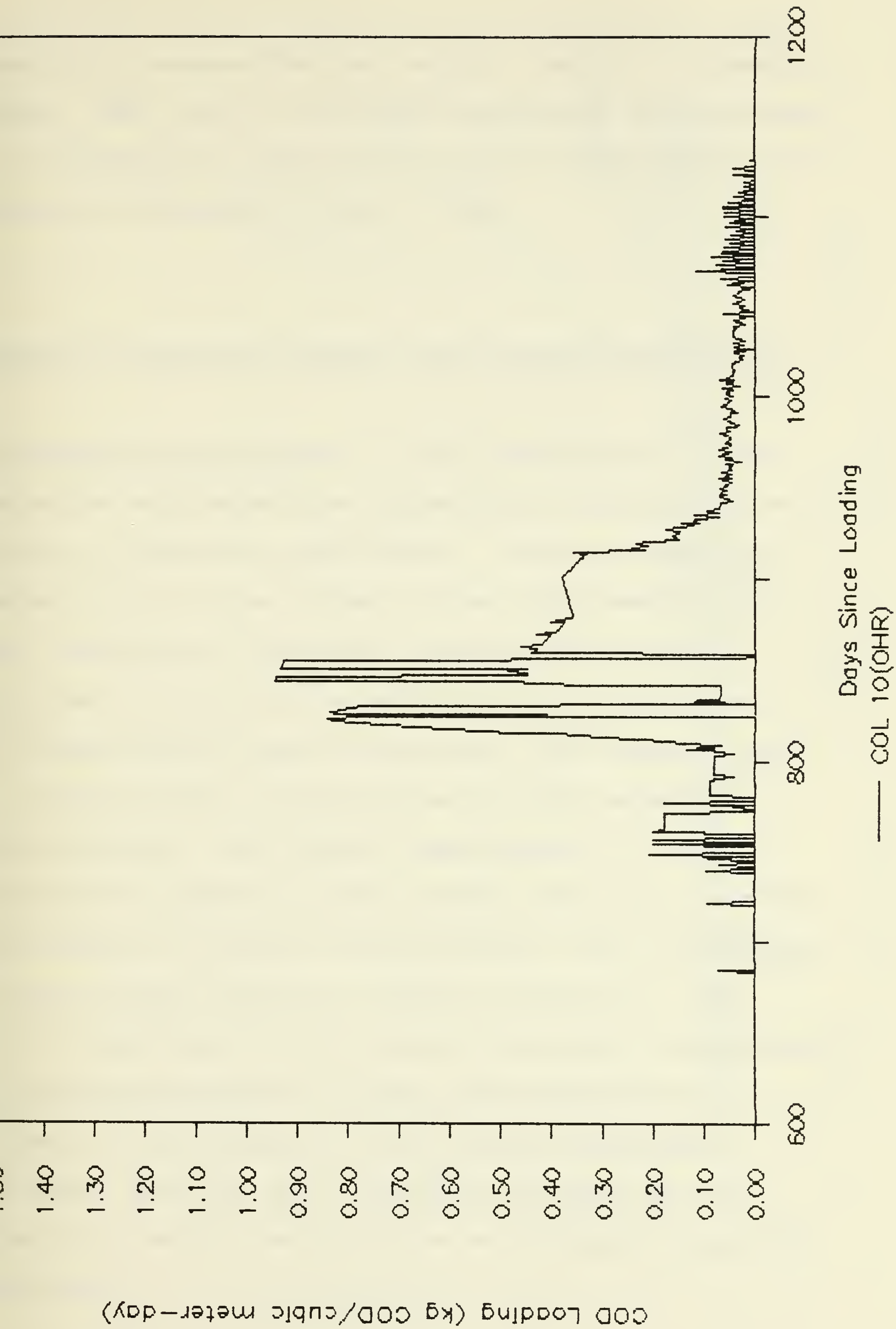
Determined from the leachate recycle volumes and the leachate COD concentrations, the organic loadings applied to the recycle columns, in terms of kg of COD applied per day per cubic meter of as placed refuse, are shown in Figures 25 through 29. Generally, the COD loadings applied were similar among all five recycle columns, and remained at rates less than 1.00 kg COD per cubic meter-day. Such rates have been found to be optimal in numerous bench-scale


1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
COD Loading (kg COD/cubic meter—day)
600
800
1000
1200
Days Since Loading
COL 1(CR)


COD Loading (kg COD/cubic meter-day)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
600
800
1000
1200
Days Since Loading
COL 6(OR)


COD Loading (kg COD/cubic meter-day)
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
800
1000
1200
Days Since Loading
COL 7(OLR)

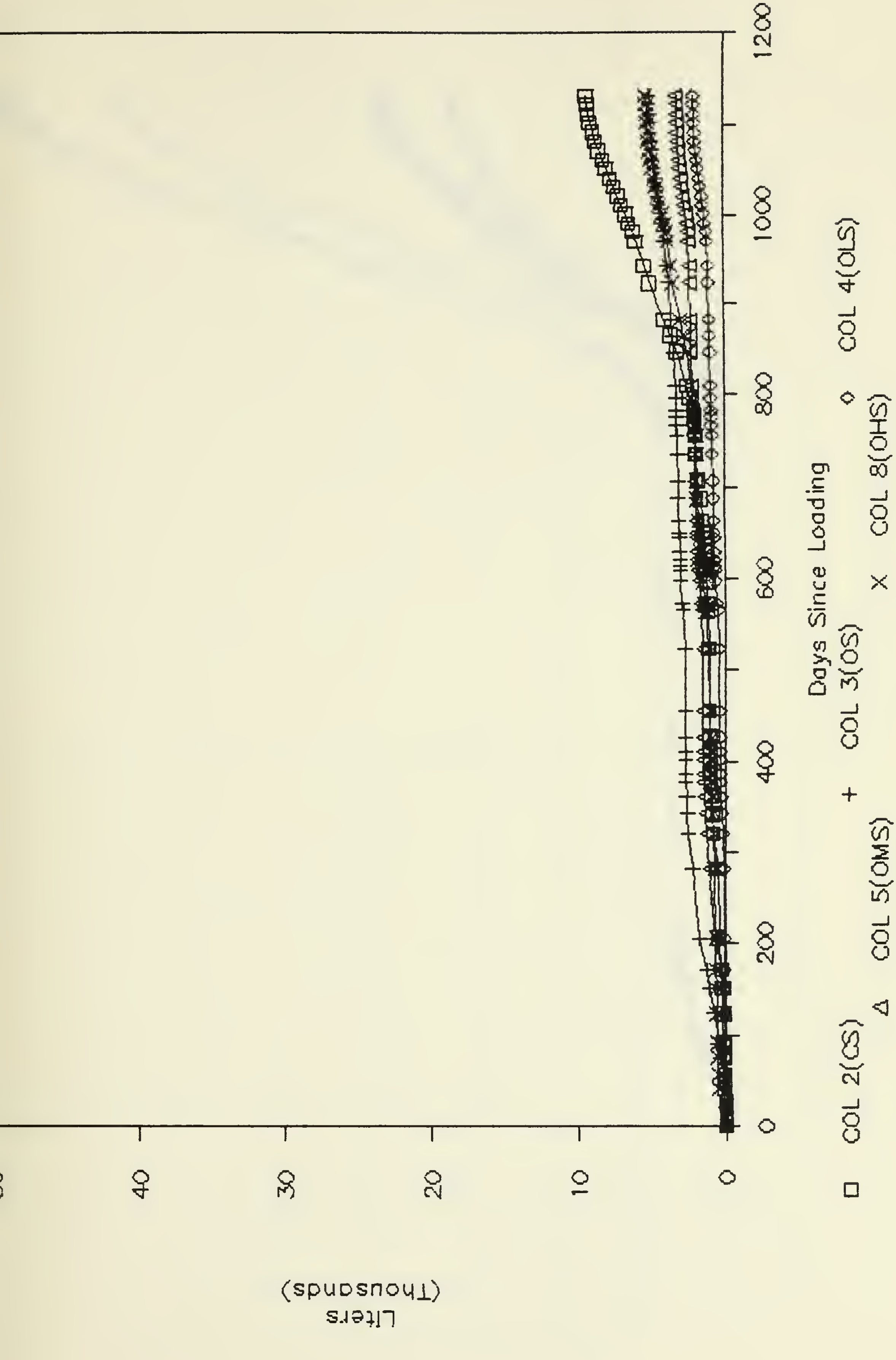

COD Loading (kg COD/cubic meter-day)
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
800
1000
1200
Days Since Loading
COL 9(OMR)


COD Loading (kg COD/cubic meter-day)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
600
800
1000
1200
Days Since Loading
COL 10(OHR)

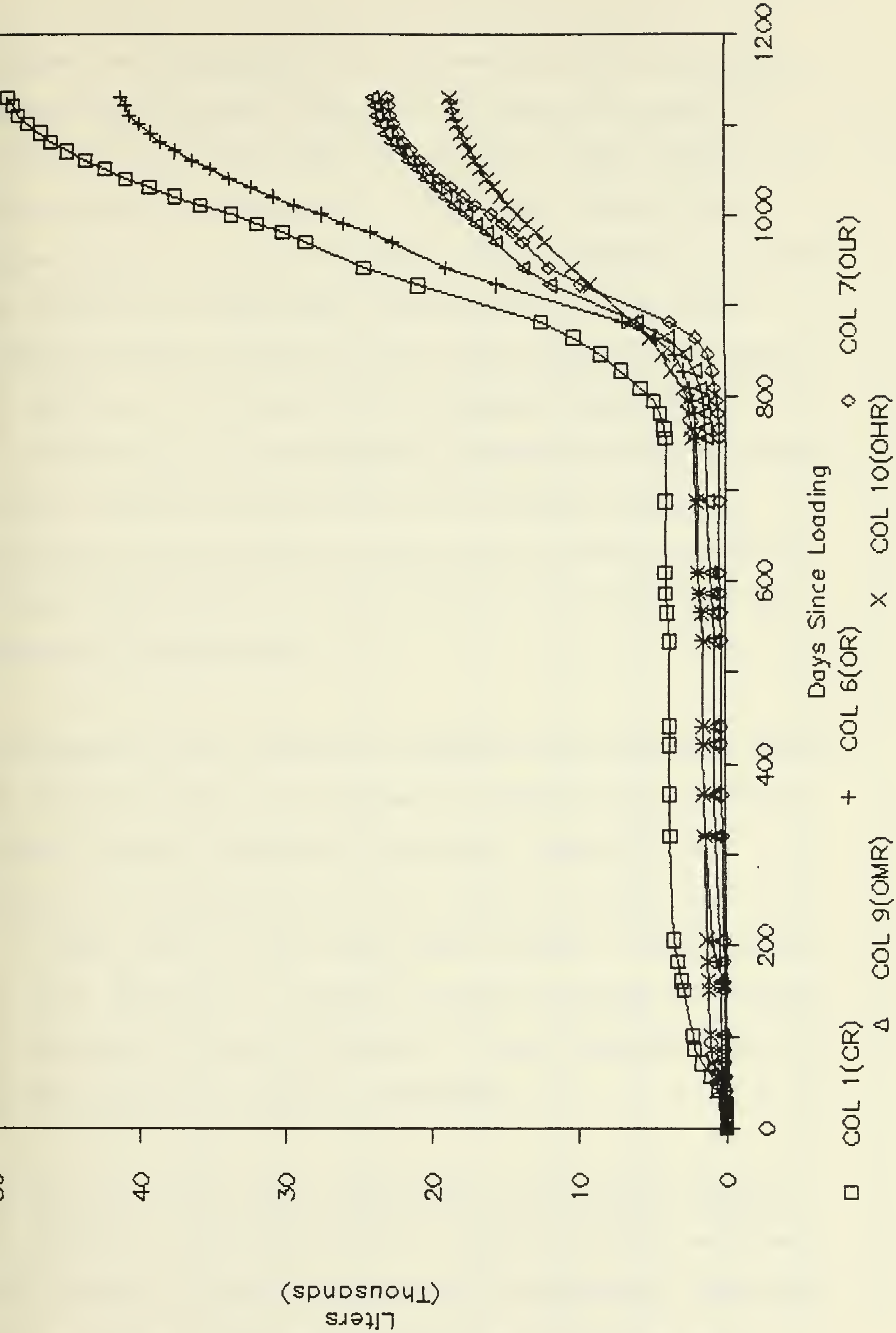
anaerobic processes treating landfill leachate (Pohland and Harper, 1985), and in the present experiment did not appear to be excessive as indicated by the relatively prolific gas production measured in Column 1 (CR).

Effects of Pollutant Loadings and Leachate Recirculation

Gas Production and Quality - Early measurements of gas production and composition reflected the transition from aerobic to anaerobic stabilization. Gaseous oxygen was present in all of the columns during approximately the first 300 days, as indicated in Figures 15 through 24. Contained in the air entrained within the interstices of the refuse during loading operations, this oxygen allowed for initial aerobic stabilization with the release of carbon dioxide. The eventual displacement of this interstitial oxygen by carbon dioxide led to the transition from aerobic to anaerobic stabilization, with a concomitant decrease in gas production (Figures 30 and 31). The relative durations of this transitional phase, as indicated by the time required for initial gas production to decrease, is attributable to the leachate management strategies employed, and illustrates the accelerating affects of leachate recirculation on microbially-mediated stabilization.



Liters (Thousands)
0
10
20
30
40
Days Since Loading
0
200
400
600
800
1000
1200
COL 2(CS)
COL 5(OMS)
COL 3(OS)
COL 8(OHS)
COL 4(OLS)


Liters (Thousands)
0
10
20
30
40
Days Since Loading
0
200
400
600
800
1000
1200
□ COL 1(CR)
+ COL 6(OR)
◇ COL 7(OLR)
Δ COL 9(OMR)
X COL 10(OHR)

Hydrogen detected within the columns during the ensuing anaerobic period was indicative of the early stages of volatile fatty acid formation and of the near absence of active methane fermentation. After Days 200 and 400, respectively, little gas production was observed in either the recycle or single pass columns prior to the ninth seeding procedure which was the first seeding to include the addition of pH-neutralized leachate (Appendix II). As the introduction of methanogens through the revised seeding process continued between Days 775 and 898, dramatic increases in gas production and quality were observed as methane fermentation of the volatile acid intermediates became well established.

Containment of gas producing substrate and nutrients within the recycle columns, as opposed to substrate and nutrient washout through single pass leaching, resulted in cumulative gas production in the recycle columns of 3.5 to 11.1 times that of the single pass columns, as measured on Day 1131 (Table 16). Figures 30 and 31 further illustrate the magnitude of this difference in gas production due to the difference in leachate management.

In the case of both the single pass and recycle columns, gas production from the control columns clearly exceeded that from any of the test columns, as expected. Among the recycle columns, the next highest gas production was

Table 16 Cumulative Gas Production (L at standard temperature and pressure)

Recycle Columns						Single Pass Columns				
COL 1	COL 6	COL 7	COL 9	COL 10	Days Since Loading	COL 2	COL 3	COL 4	COL 5	COL 8
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	10	0	0	0	0	0
0	0	0	0	0	20	0	0	0	0	0
0	0	0	0	0	23	0	0	0	0	0
61	0	0	0	12	26	0	0	0	0	21
599	40	23	213	654	41	126	57	80	54	462
1036	63	23	236	733	56	168	184	88	56	516
1692	85	45	290	938	75	188	403	88	56	573
2165	93	50	308	1061	91	210	546	88	56	606
2287	96	50	309	1094	123	230	784	88	56	613
2832	97	60	351	1161	151	273	1067	88	56	613
3004	172	60	367	1193	172	320	1201	89	241	637
3253	645	80	390	1243	206	445	1723	96	684	664
3519	929	107	390	1273	282	532	2207	97	1056	723
3766	1311	167	641	1366	321	817	2501	143	1245	834
3792	1384	205	729	1438	342	898	2579	227	1314	917
3793	1482	237	735	1482	361	950	2633	283	1378	980
3793	1536	237	737	1482	376	1009	2699	342	1446	1040
3793	1541	237	768	1487	386	1033	2704	345	1457	1052
3924	1684	298	845	1591	401	1037	2704	346	1468	1057
4012	1783	365	936	1732	411	1045	2704	348	1468	1057
4039	1793	388	1011	1831	427	1061	2705	387	1471	1082
4058	1856	398	1211	1995	456	1087	2705	393	1471	1102
4066	1980	413	1316	2211	523	1119	2716	404	1474	1146
4166	2059	457	1400	2317	565	1184	2840	532	1575	1311
4446	2138	467	1420	2394	573	1211	2912	629	1637	1404
4874	2245	586	1518	2536	597	1247	3010	683	1728	1467
5741	2411	743	1692	2851	609	1264	3017	695	1842	1519
7072	2863	901	2060	3698	613	1272	3020	700	1853	1527
8446	3412	1145	2685	4249	621	1303	3025	707	1853	1583
10298	4736	2007	3878	5091	630	1342	3047	712	1853	1633
12545	6978	3758	5959	6339	645	1397	3059	724	1874	1677
20916	15519	9866	11881	9163	651	1425	3071	729	1879	1696
24596	19025	11994	13703	10389	663	1509	3096	749	1894	1757
28566	22640	13733	15565	12240	687	1621	3126	774	1927	1849
30142	24121	14412	16195	12843	707	1793	3149	780	1992	1928
31888	25989	15113	16894	13473	735	1941	3170	816	2041	1957
33644	27557	15930	17593	14104	756	1943	3191	833	2085	1960
35766	29363	17002	18418	14795	766	2026	3251	877	2152	2049
37529	30830	17816	19012	15267	777	2035	3275	882	2173	2106
39217	32297	18631	19667	15759	783	2112	3279	892	2176	2118
40882	33798	19440	20329	16226	796	2370	3296	933	2205	2193
42349	35110	20142	20934	16641	810	2582	3321	939	2214	2286
43669	36331	20773	21527	17002	847	3233	3408	974	2246	2552
44953	37508	21383	22136	17366	865	3625	3479	998	2268	2754
46024	38507	21898	22718	17712	883	4069	3568	1017	2284	2971
46752	39184	22185	23068	17951	922	5051	3730	1071	2314	3487

[illegible]

Table 16 (continued)

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10
1101	47600	39956	22545	23434	18254
1111	48323	40620	22801	23726	18498
1121	48641	40910	22877	23825	18581
1131	49013	41241	22953	23975	18711

Days Since Loading	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
941	5424	3874	1100	2319	3643
971	6011	3984	1182	2386	3784
981	6178	4010	1197	2407	3841
991	6467	4168	1314	2492	4009
1001	6674	4258	1354	2581	4144
1011	6979	4380	1437	2694	4349
1021	7186	4431	1483	2742	4429
1031	7477	4533	1591	2836	4598
1041	7744	4617	1676	2902	4706
1051	8014	4705	1768	2974	4826
1061	8269	4780	1841	3029	4916
1071	8531	4854	1916	3080	5011
1081	8750	4906	1970	3121	5079
1091	8895	4931	1994	3142	5111
1101	9102	4983	2034	3179	5187
1111	9251	5012	2053	3199	5220
1121	9297	5020	2066	3204	5226
1131	9375	5036	2071	3213	5283

observed in the test column loaded only with organic priority pollutants, Column 6 (OR). Lagging in gas production were the remaining recycle test columns, which had also received inorganic priority pollutants in the form of heavy metals. Columns 7 (OLR) and 9 (OMR) produced comparable quantities of gas even though the heavy metal loadings to Column 9 (OMR) were twice that applied to Column 7 (OLR), suggesting some ability of Column 9 (OMR) to detoxify the environment within the test cell. Following in logical order, Column 10 (OHR), which received the largest heavy metal loading, showed the apparent greatest toxic inhibition as indicated by its generation of the least amount of gas among the recycle columns. Statistical tests (Appendix IX) confirmed that, with respect to Column 1 (CR), the gas productions of Columns 7 (OLR) and 9 (OMR) were not significantly different, but that the gas production of Column 10 (OHR) was significantly below that of these lighter loaded columns.

The relative degree of toxicity experienced among the recycle columns is illustrated in Figures 32 and 33 where cumulative gas productions of the test columns are given as percentages of Column 1 (CR), and Column 6 (OR), respectively. Inhibition due to the organic loadings, particularly prior to active methane production, is evidenced by the low relative gas production of Column 6 (OR). However, as methanogenesis was established, the

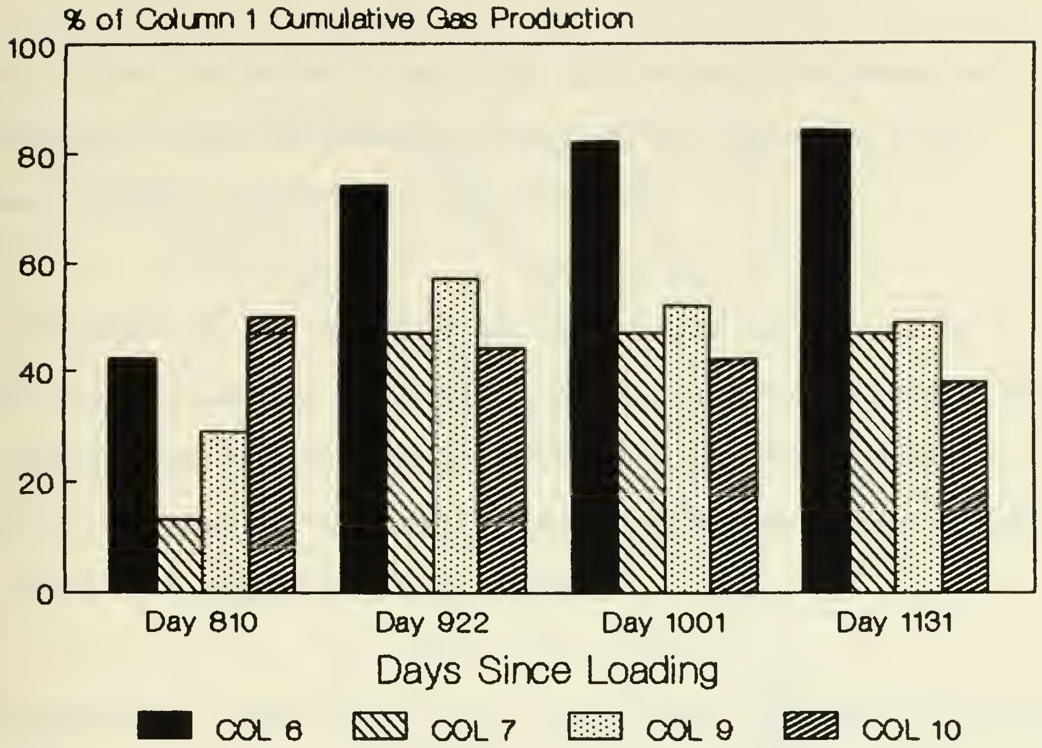


Figure 32 Recycle Test Columns, Cumulative Gas Production Relative to the Control

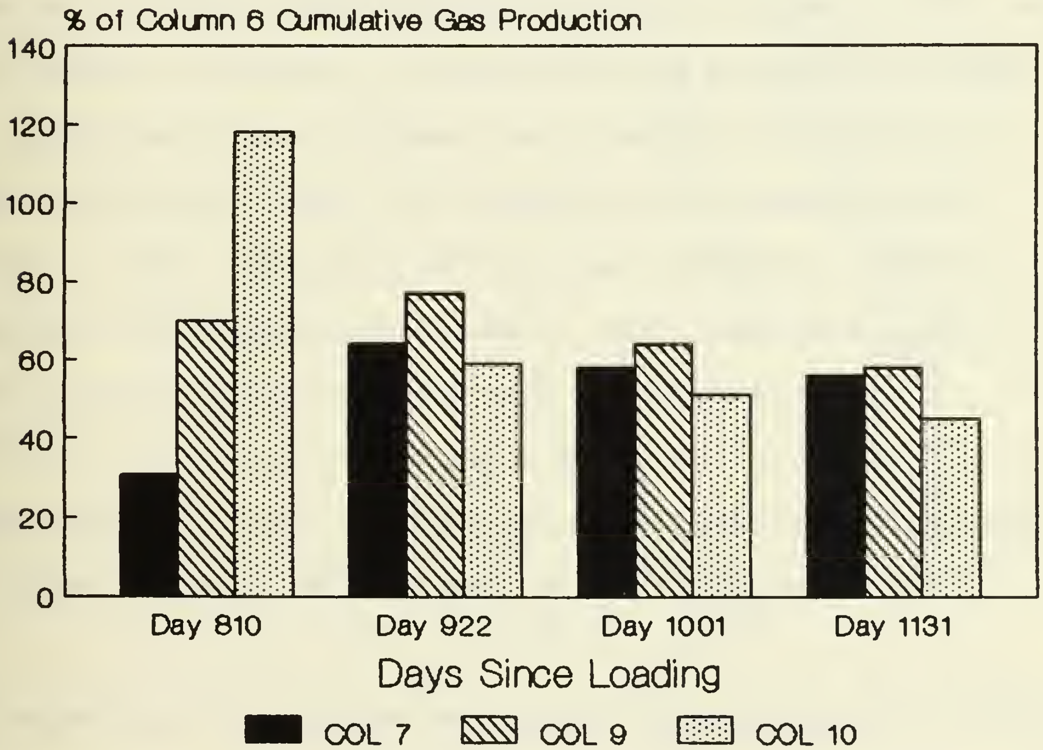


Figure 33 Recycle Columns with Inorganics, Cumulative Gas Production Relative to Column 6 (OR)

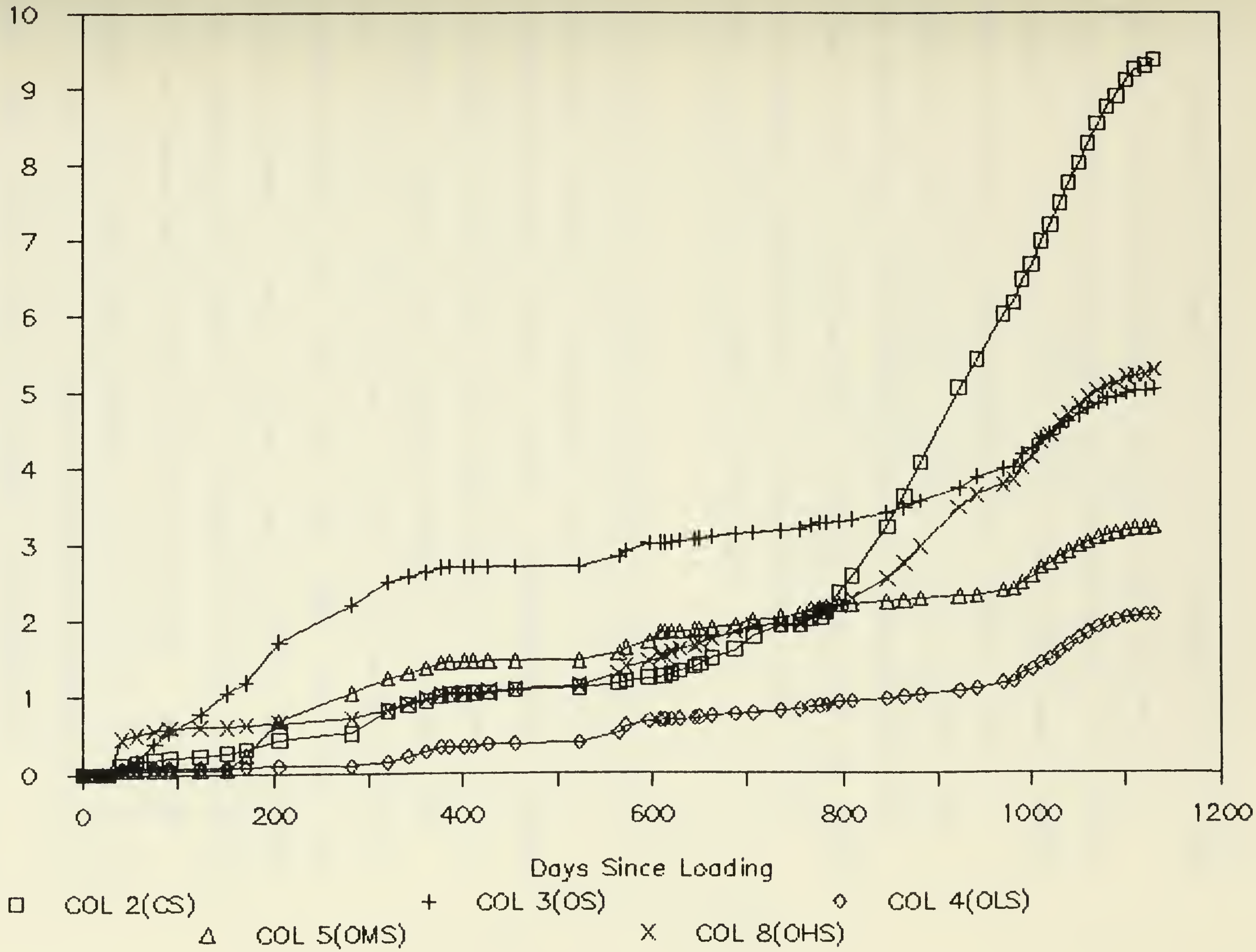
impact from the organic priority pollutants lessened as indicated by the increasing trend in gas production of Column 6 (OR) relative to the control.

Both Figures 32 and 33 show an increasing impact of the heavy metal loadings as methane production continued. This was likely due to increased permeation of the inorganic pollutants into the initially uncontaminated zones between the layers of applied metal sludge.

Gas production among the test single pass columns followed a less obvious pattern. Shown on an expanded scale, (Figure 34), all of the loaded single pass columns produced substantially less gas than the control, Column 2 (CS), as anticipated. However, the greatest gas production among the single pass test columns was observed from Column 8 (OHS) while the lowest gas production was observed from Column 4 (OLS), opposite of what was logically expected. However, with respect to Column 2 (CS), the total gas production of Column 8 (OHS) was not significantly different from that of Column 3 (OS), but the gas production of Column 4 (OLS) was significantly below that of Column 5 (OMS) (Statistical tests in Appendix IX).

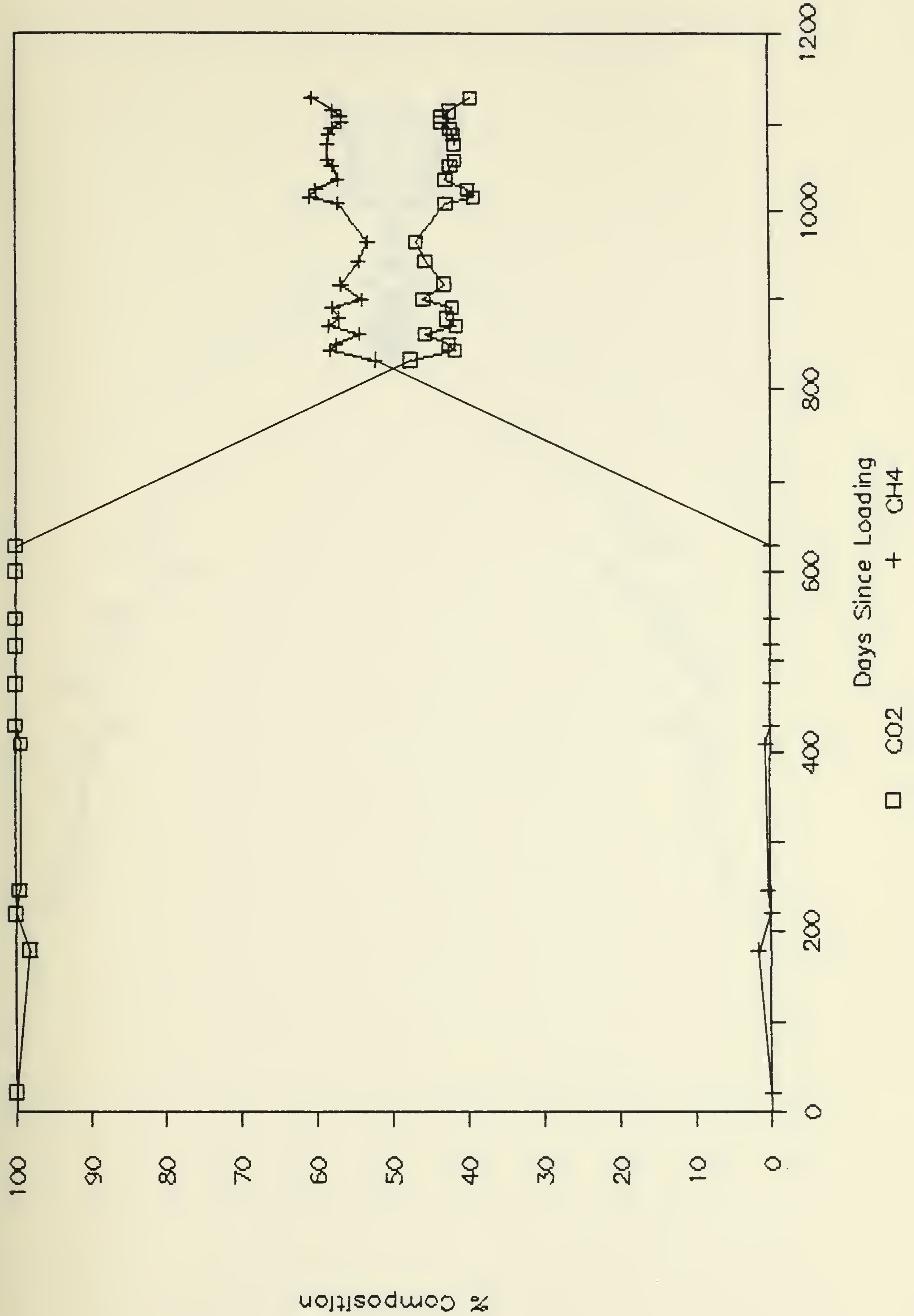
In comparing the differences in total gas production among the single pass columns with the total produced by Column 1 (CR), the gas production of the loaded single pass columns

Cumulative Gas Production (@ STP), Single Pass Columns
(expanded scale)



was significantly lower than that from Column 2 (CS). But, cumulative gas production among the loaded columns was not significantly different with the exception of the gas production of Column 4 (OLS) which was significantly below that of the other loaded single pass columns. This comparison with the control recycle column suggests that the operational contingencies may have overshadowed the effects that the varying metal loadings may have had on the gas producing capabilities of those single pass columns which received the inorganic pollutants.

The effects of the leachate management strategies and pollutant loadings on gas quality during the methane fermentation phase are more vividly represented by Figures 35 through 44 which show gas compositions for the ten columns in terms of the relative amounts of methane and carbon dioxide. With respect to each pairing of similarly loaded columns (i.e., (C), (O), (OL), (OM), and (OH)), the recycle column, in each instance, more rapidly established a gas composition typical of a landfill actively undergoing methane fermentation (40 % CO_2 and 60 % CH_4). Although delayed, the steady improvement in gas quality observed in all of the single pass columns suggested attenuation of the toxic heavy metals and/or a gradual acclimation to remaining concentrations. Further, the faster improvement in gas quality measured in Column 2 (CS) as compared with the test single pass columns reflected the inhibitory



% Composition
Days Since Loading
CO2
CH4
0
10
20
30
40
50
60
70
80
90
100
0
200
400
600
800
1000
1200

Figure 36 Normalized Gas Composition, Column 2 (CS)

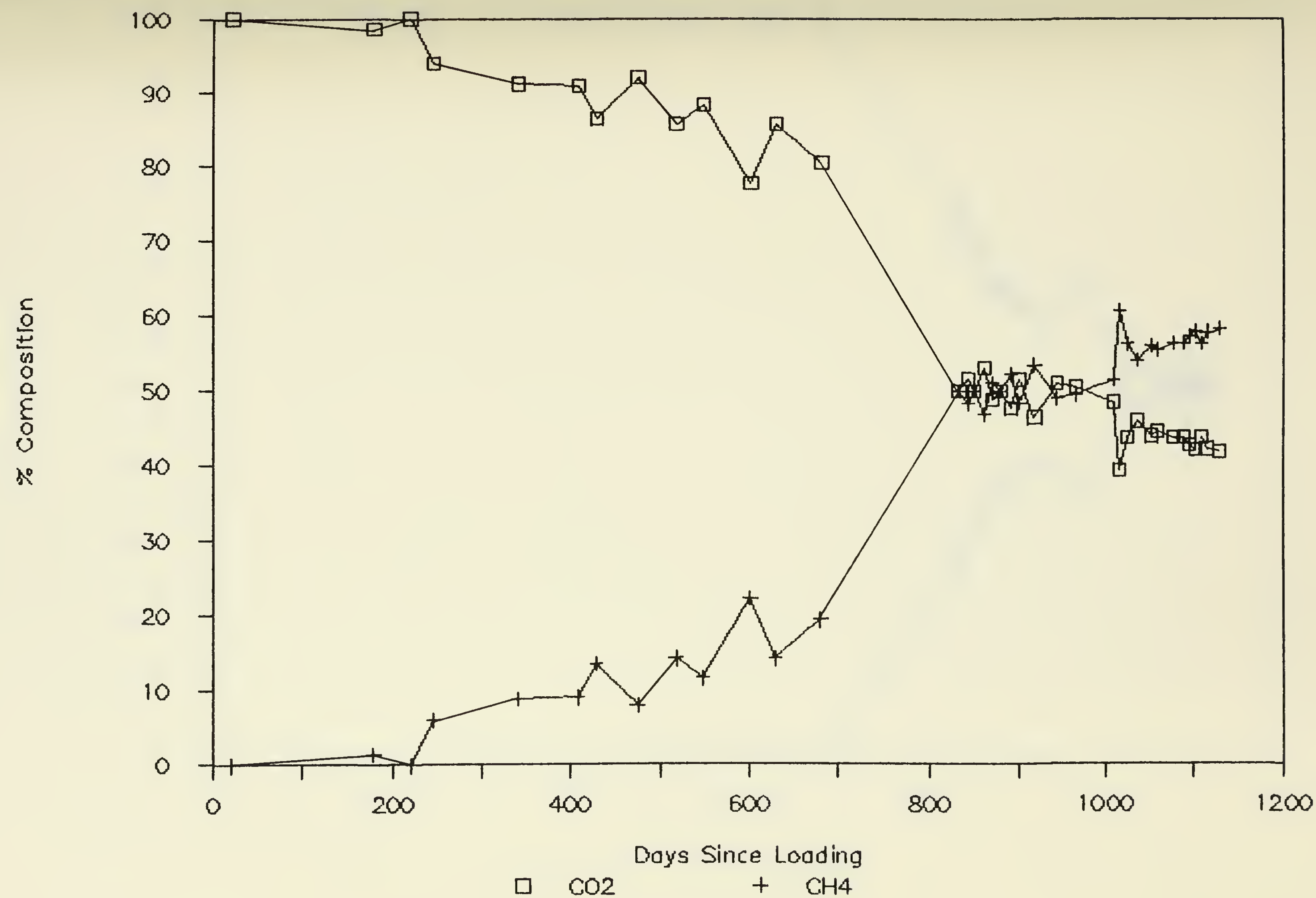


Figure 37 Normalized Gas Composition, Column 3 (OS)

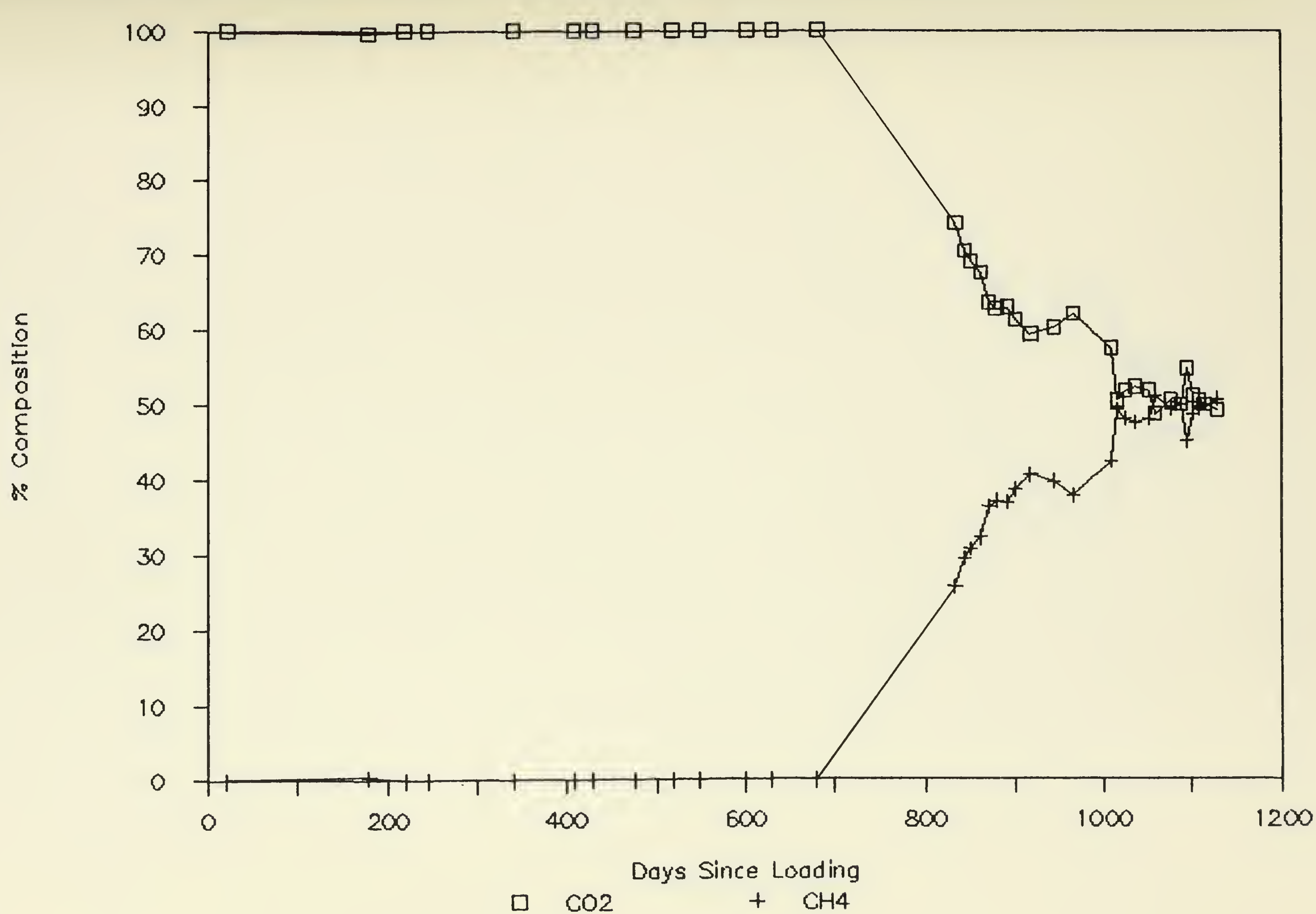


Figure 38 Normalized Gas Composition, Column 4 (OLS)

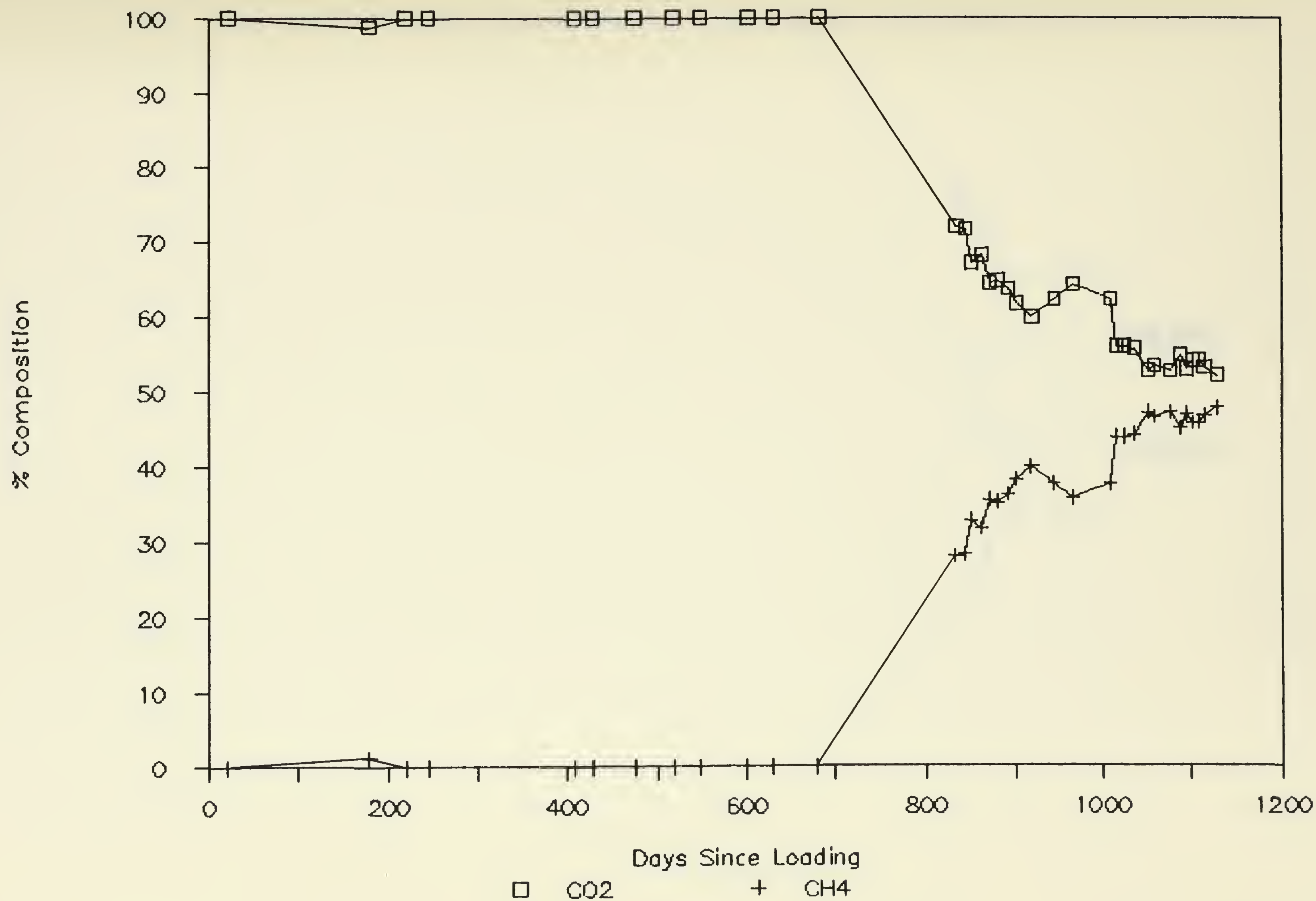


Figure 39 Normalized Gas Composition, Column 5 (OMS)

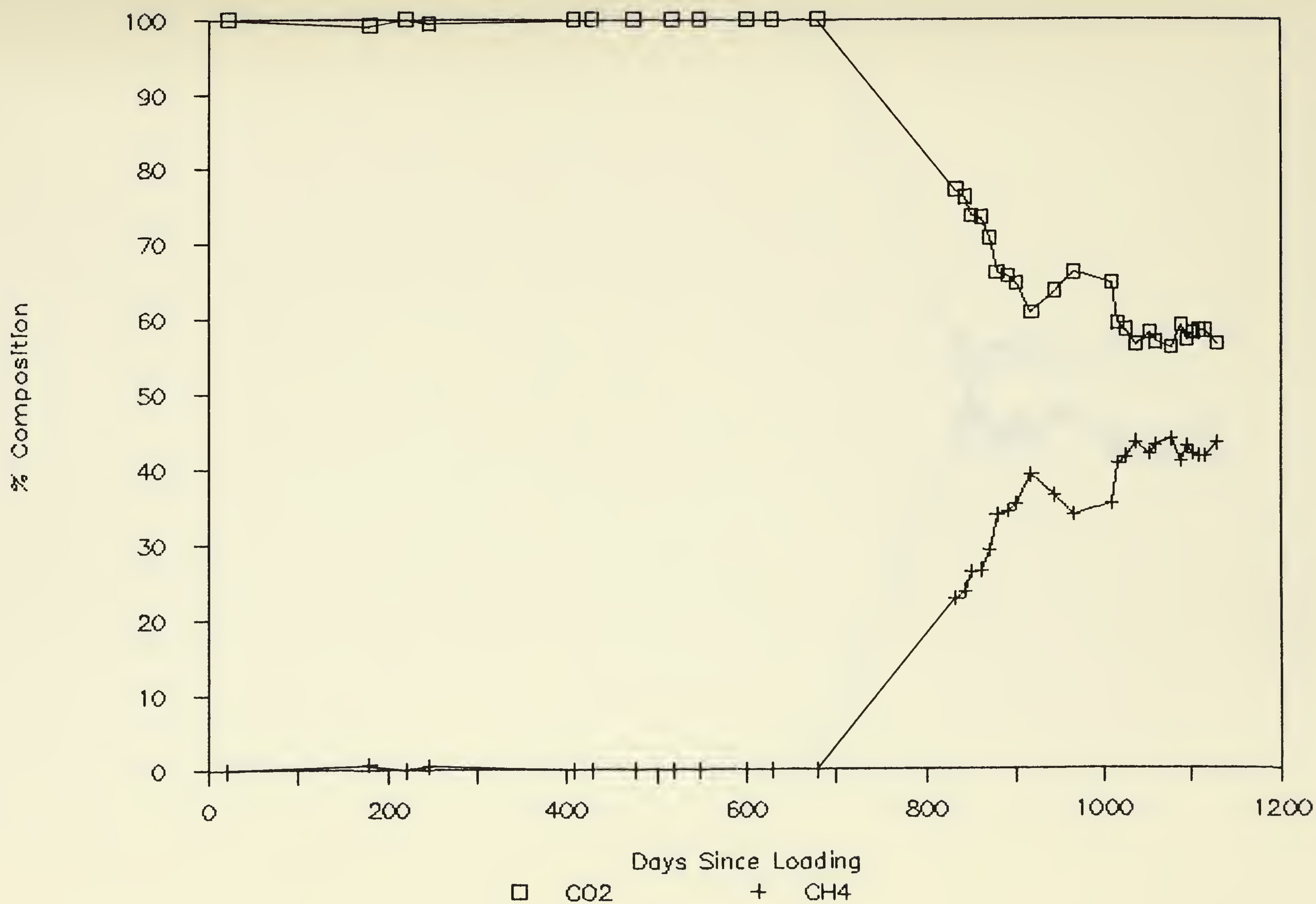


Figure 40 Normalized Gas Composition, Column 6 (OR)

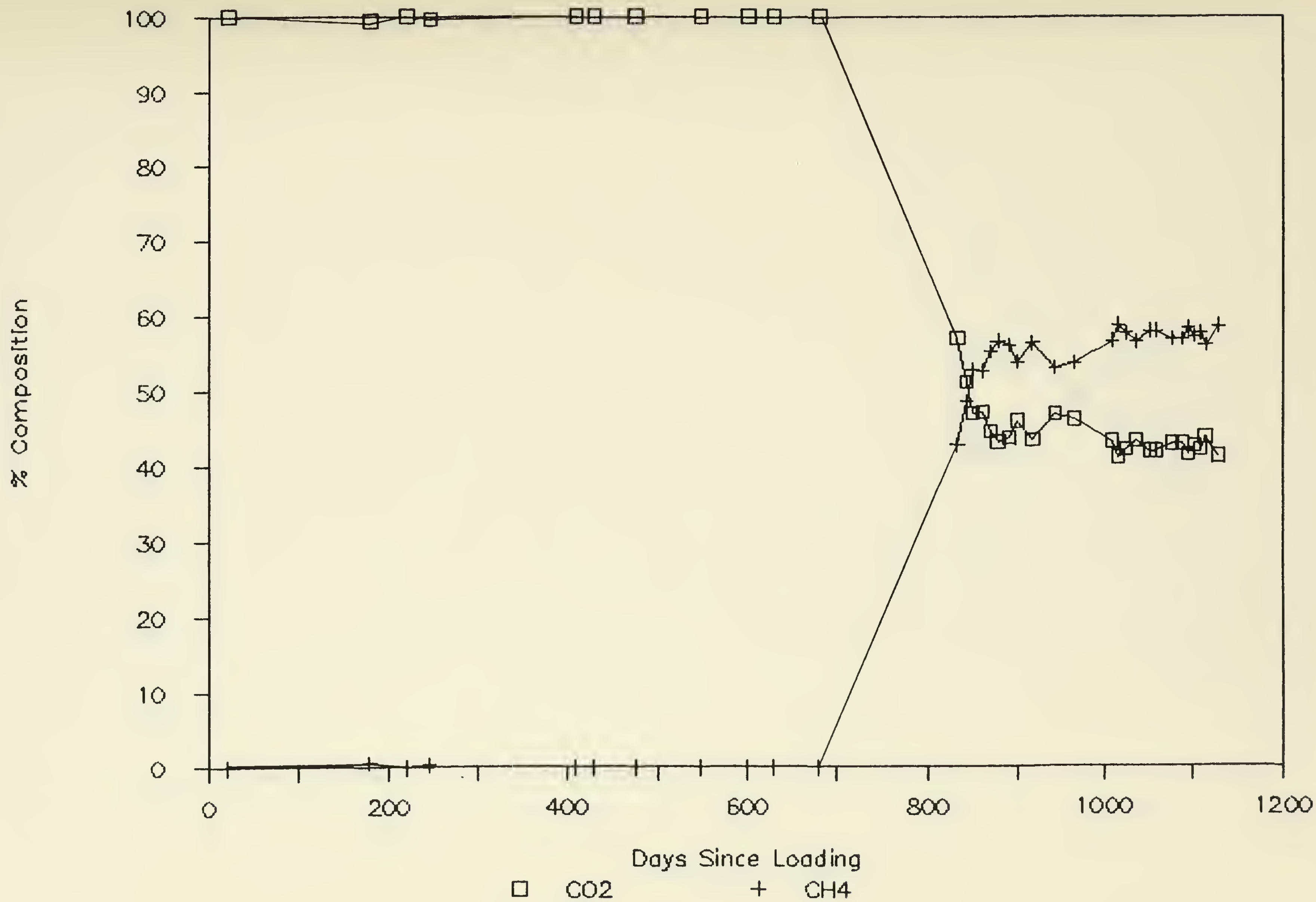


Figure 41 Normalized Gas Composition, Column 7 (OLR)

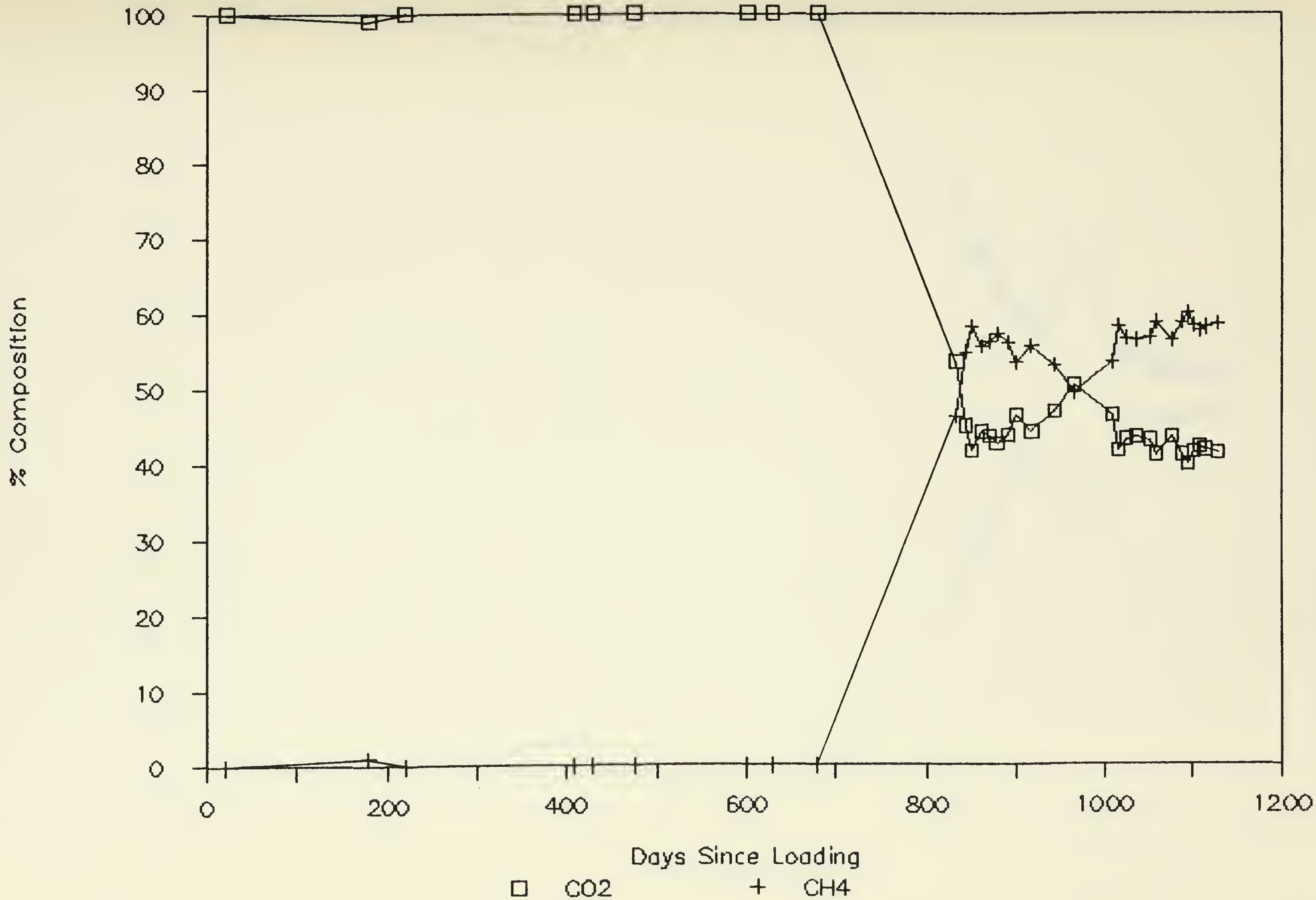


Figure 42 Normalized Gas Composition, Column 8 (OHS)

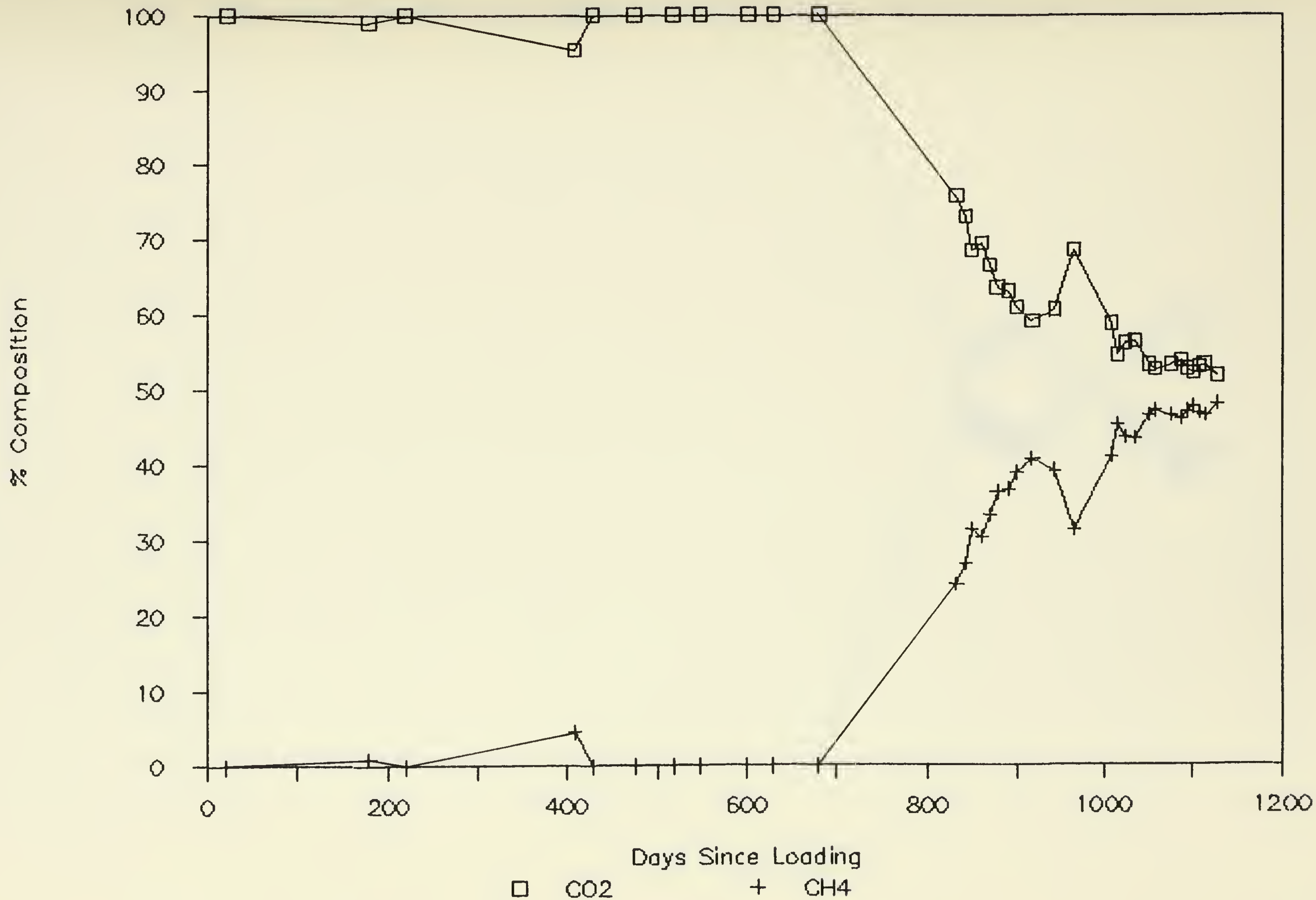


Figure 43 Normalized Gas Composition, Column 9 (OMR)

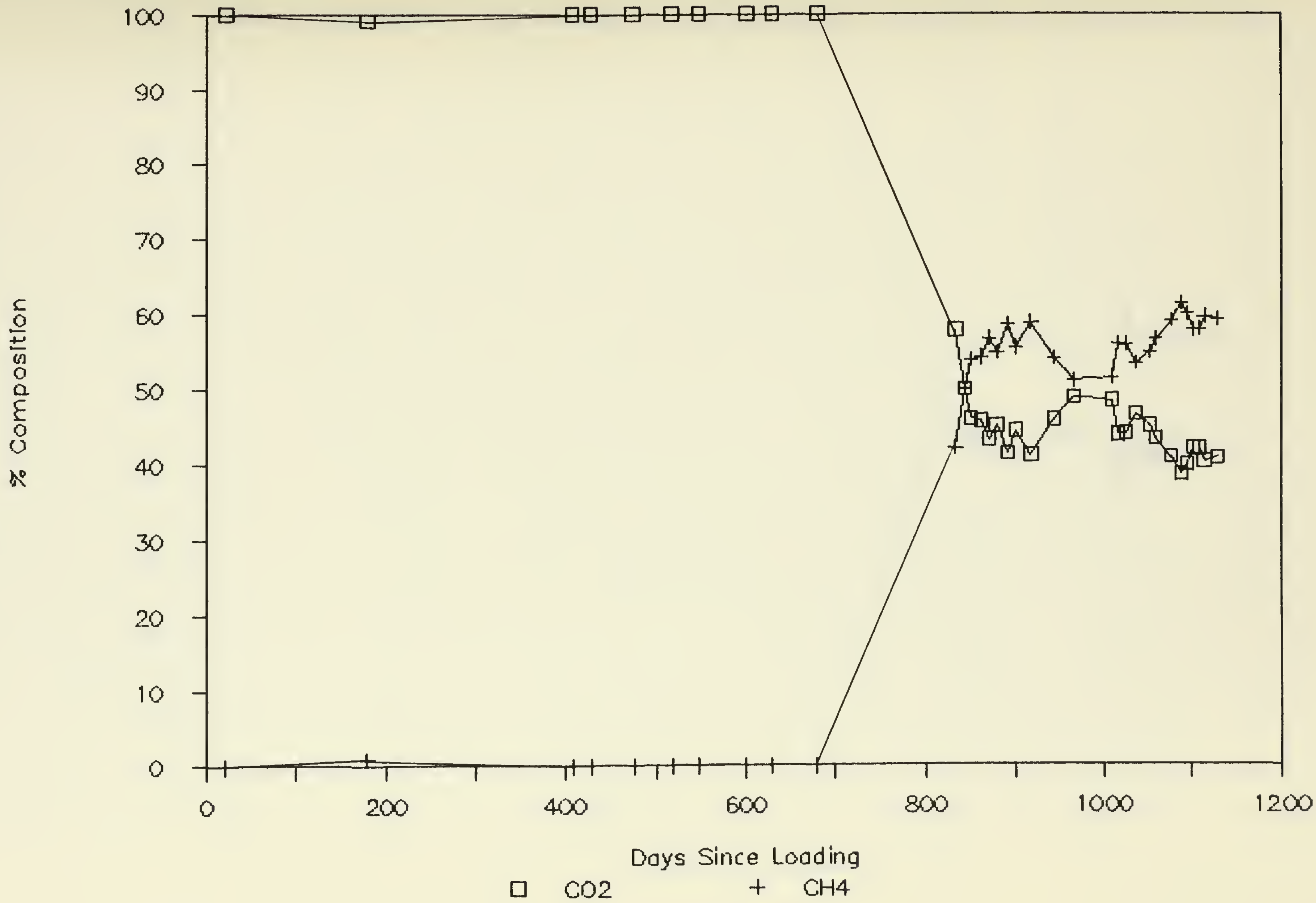
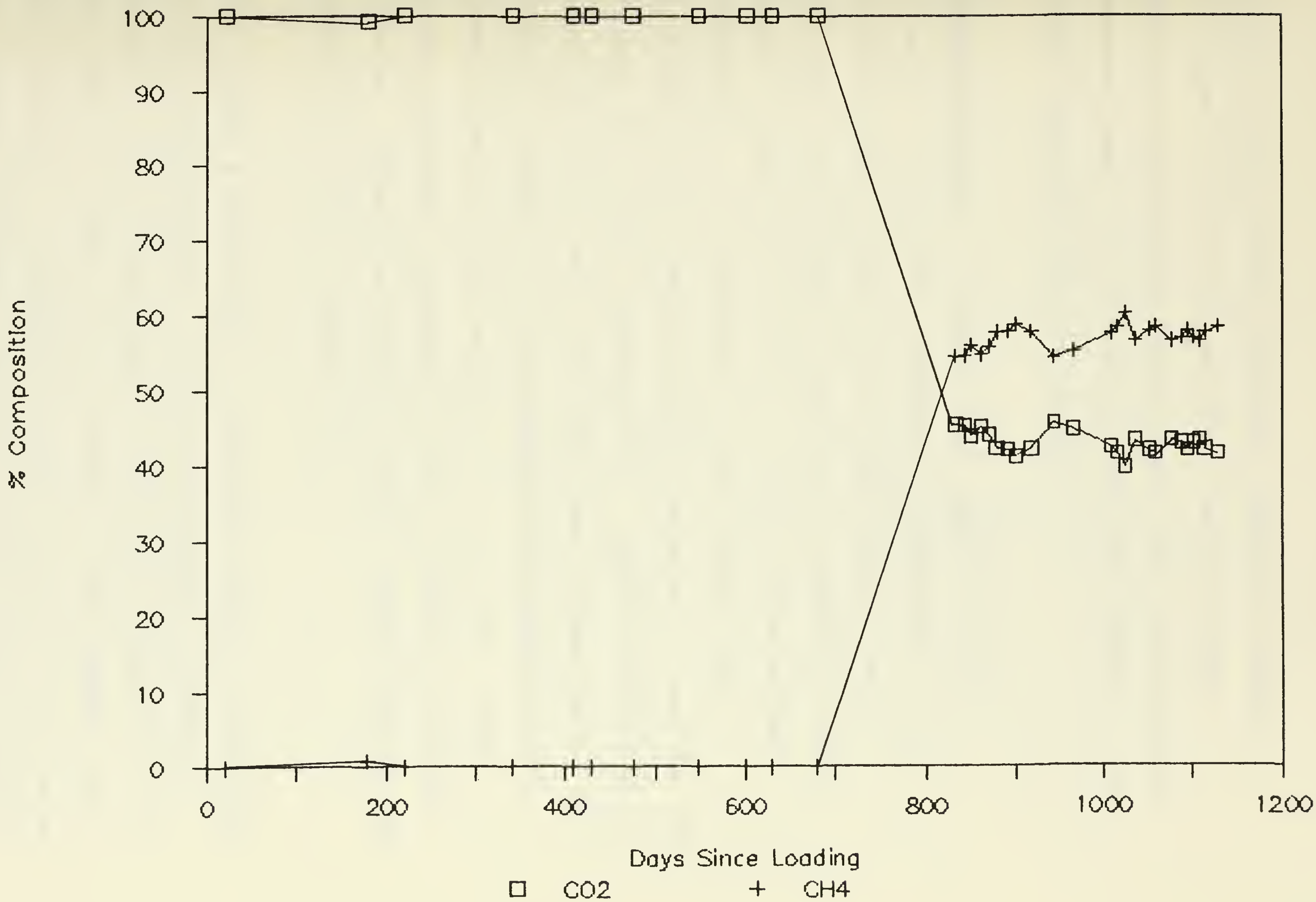


Figure 44 Normalized Gas Composition, Column 10 (OHR)



effects of the priority pollutant loadings. However, increases in gas quality among the recycle columns generally followed one common trend, again reflecting the lessened impact of the priority pollutant loadings on the columns employing leachate recycle.

Leachate Quality - Indicative of leachate organic strength, leachate COD concentrations measured in the recycle columns (Figure 12) followed patterns which reflected the biological conversion of substrate to end-products (mainly CO_2 and CH_4). During active methane fermentation, the conversion of the volatile acid intermediates was demonstrated by decreases in leachate TVA (Figure 14) and COD concentrations. Similar patterns were somewhat obscured among the single pass columns due to the effects of washout, yet the measured gas production from these columns provided evidence of a continued, albeit slower biological conversion of COD to methane and carbon dioxide. (Appendixes IV and V contain leachate COD and TVA analytical results, respectively.)

Even though a sufficiency of substrate existed, as measured by TVA concentrations, the rate of substrate conversion among the single pass columns significantly lagged that of the similarly loaded recycle columns. This suggests that the difference in microbial activity was due to differences in leachate management strategies rather than the original

column contents.

After Day 1000, dramatic decreases were noted in the leachate COD and TVA concentrations measured in the control columns indicating that more complete methane fermentation and stabilization was occurring in these unstressed columns. Following in apparent accordance with their respective loadings (low, medium and high) the leachate TVA and COD concentrations from those recycle columns loaded with heavy metals were also decreasing, although at a much slower rate. At any rate, the decreasing trends in leachate TVA concentrations noted in all the recycle columns suggested an ability of these columns to adjust to the priority pollutant loadings and convert the available substrate, thus reducing the organic strength/pollution potential of the leachate.

The effects of the phenomenon "washout" on leachate constituent concentrations in the single pass columns is perhaps best illustrated by the pattern followed by leachate chloride concentrations. Chloride, being a biologically stable anion, serves as a conservative tracer. As expected, leachate chloride concentrations measured in the recycle columns, after an initial leaching and adjustment period, maintained relatively constant levels, as illustrated in Figure 45. In contrast, Figure 46 shows

Figure 45 Leachate Chloride Concentrations, Recycle Columns

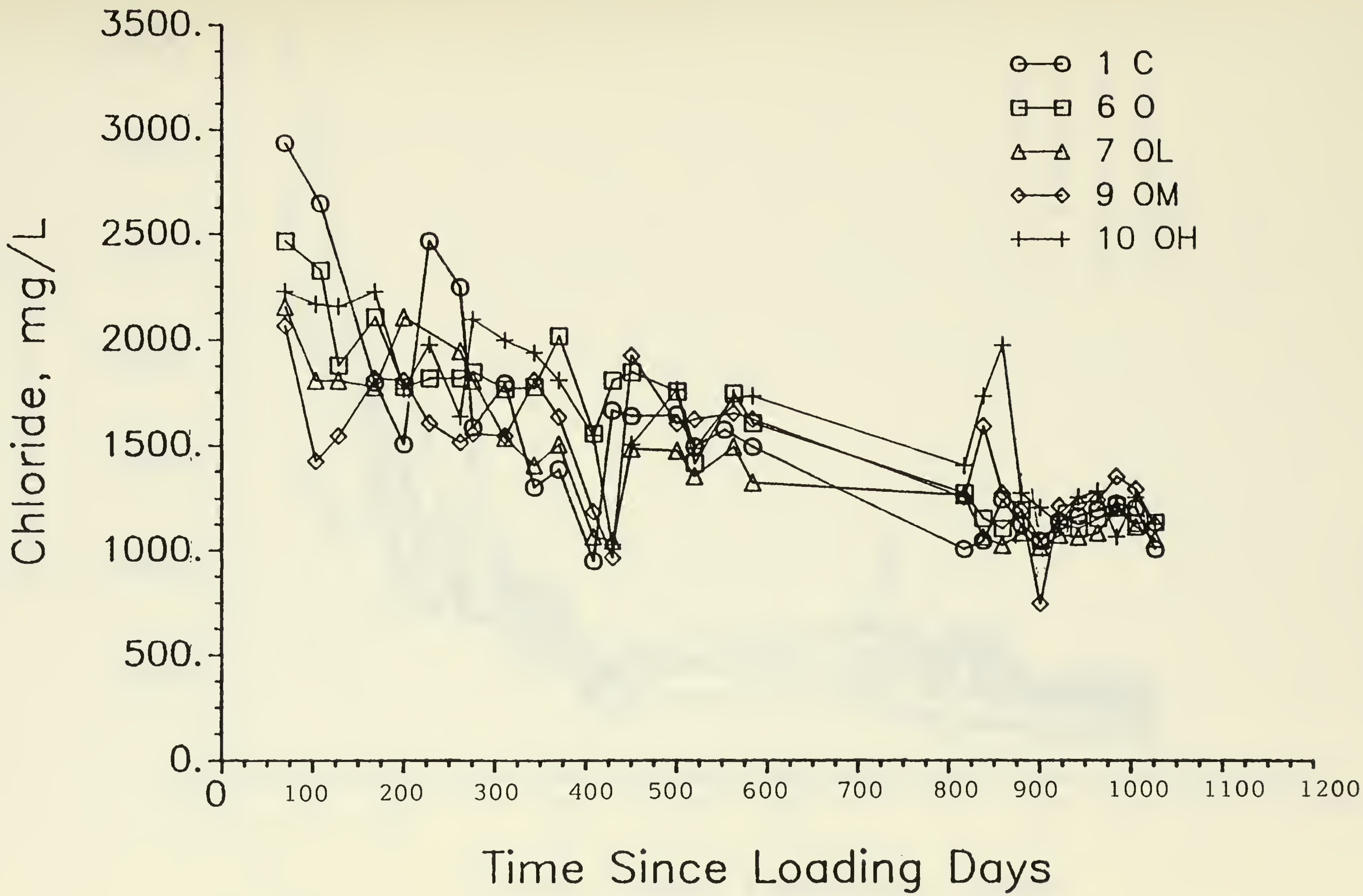
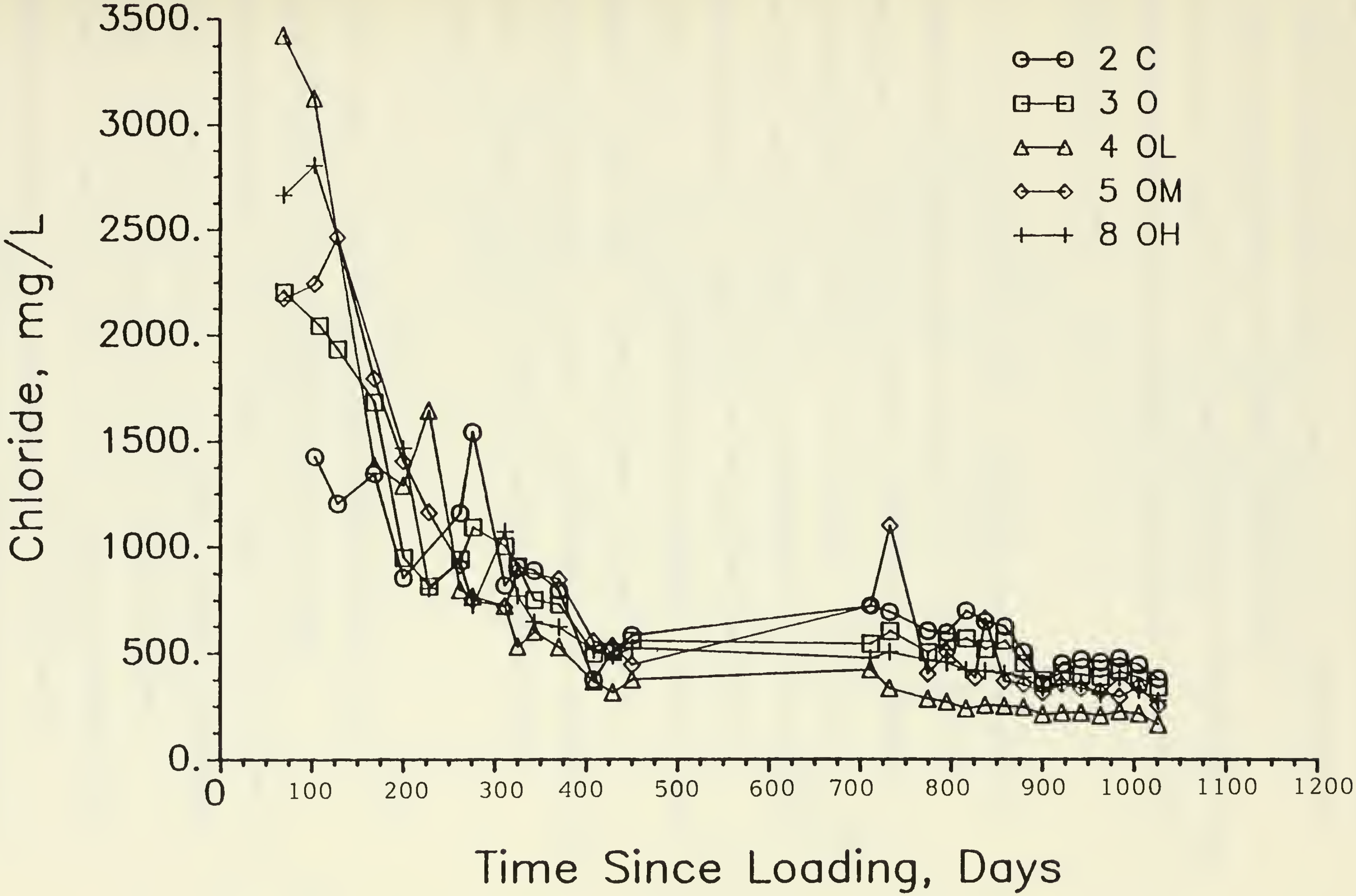


Figure 46 Leachate Chloride Concentrations, Single Pass Columns



a pronounced reduction of leachate chloride concentrations with time in the single pass columns. It is important to note that the lessening of leachate constituent concentrations caused by this washout effect represents the movement out of the waste matrix of untreated, potentially polluting constituents.

Prior to approximately Day 800, fermentations leading to the formation of the volatile fatty acid intermediates predominated. During this period leachate pH (Figures 9 and 10) buffered in the 5.0 to 5.5 range. Alkalinity levels during this same period, in the leachates of the recycle columns (Figure 47), although showing some analytical perturbations, remained relatively constant. Within the leachates of the single pass columns, a decline in alkalinity (Figure 48), likely attributable to washout, was detected. (Appendix VI contains leachate alkalinity results.)

With the onset of active methane fermentation after approximately Day 800, leachate volatile acid concentrations declined, allowing a shift in the buffering system to a more neutral pH. Although leachate pH began a gradual climb as the conversion of volatile acids continued, it was not until Day 913 that any leachate pH reached the value of 6.0 (Appendix VII contains pH measurements). Since methanogenic bacteria are generally

Figure 47 Leachate Alkalinity, Recycle Columns

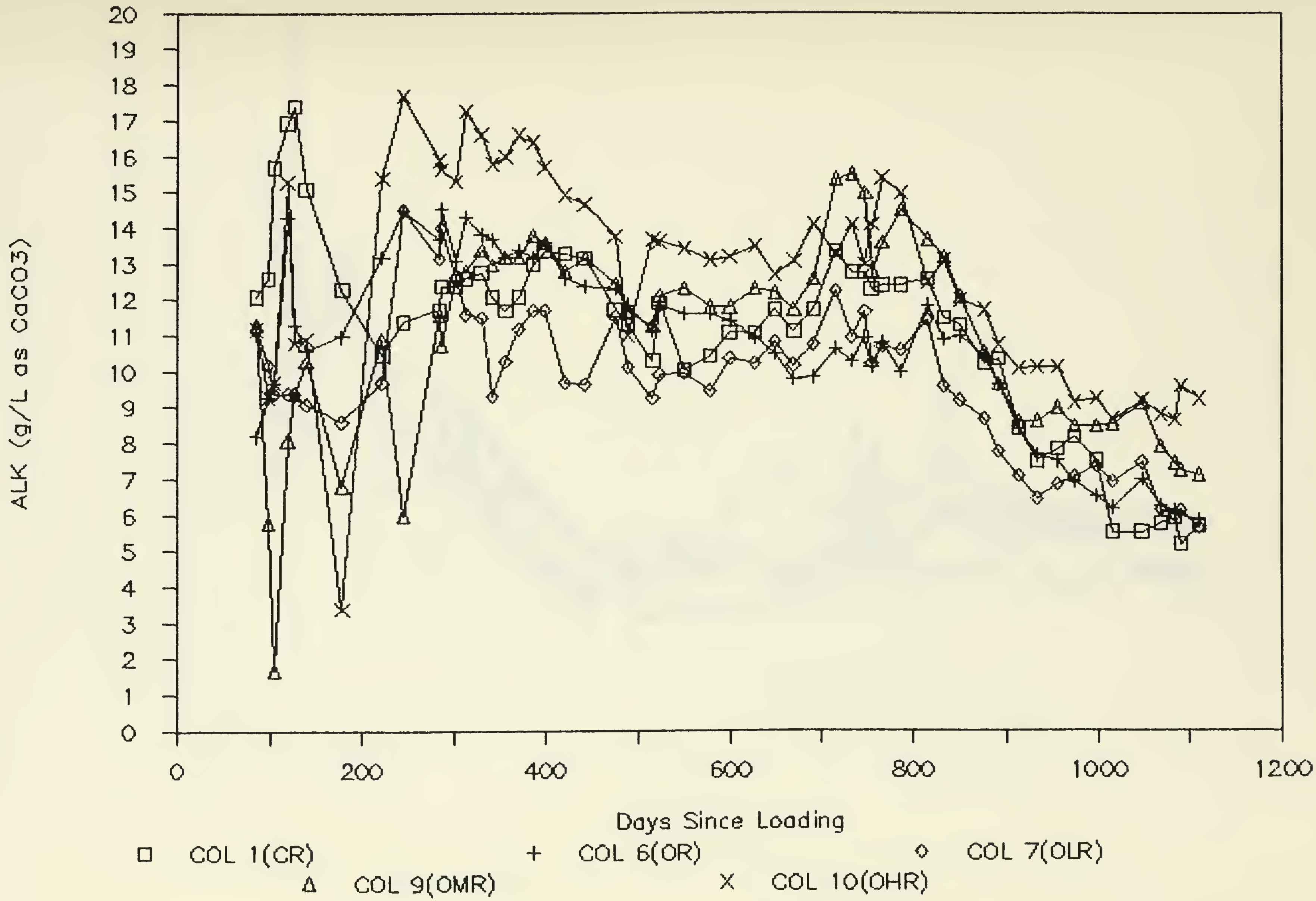
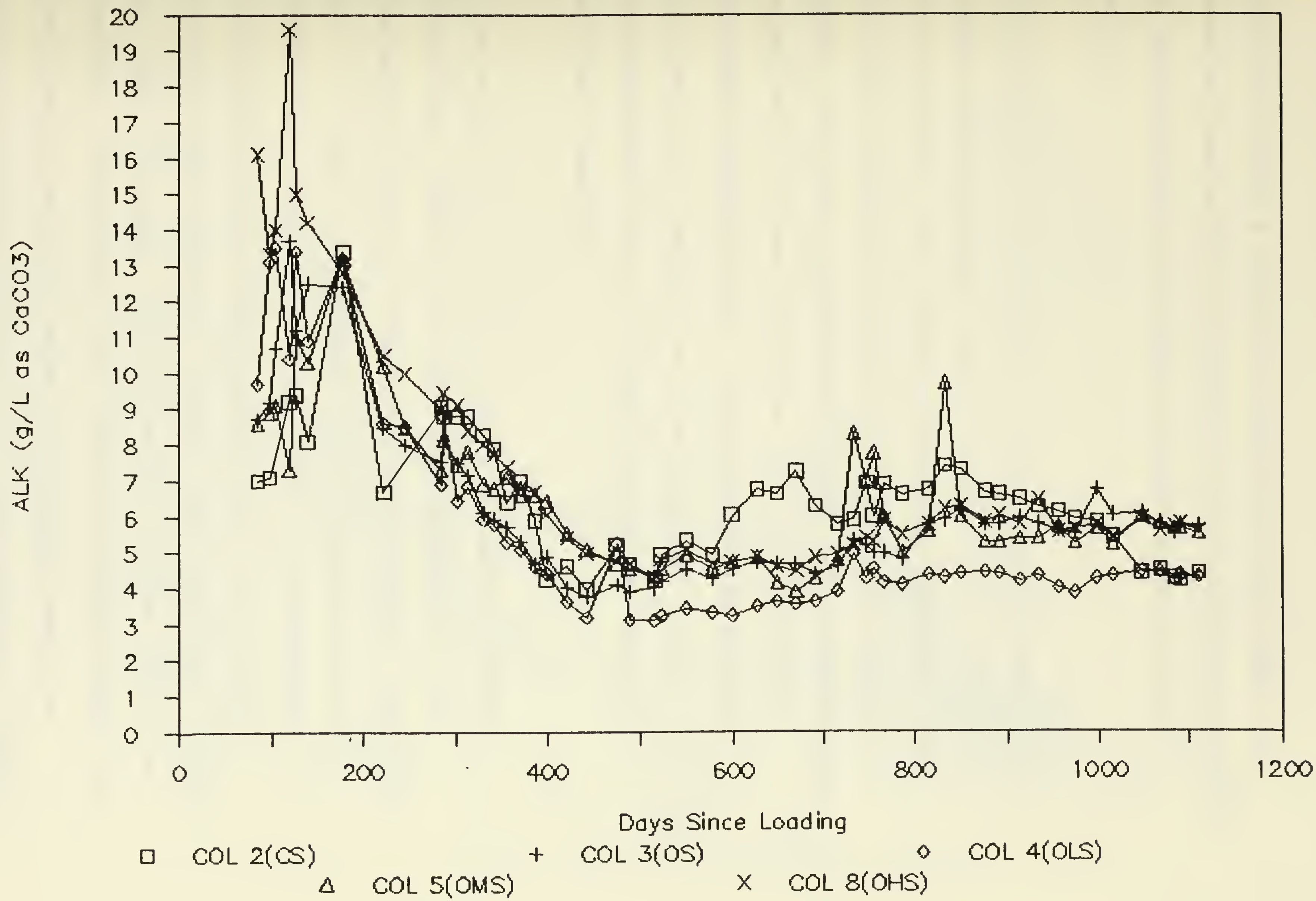


Figure 48 Leachate Alkalinity, Single Pass Columns



inhibited below a pH of 6.2 (Grady and Lim, 1980), it appeared that methane fermentation may have been occurring in growing pockets of viable bacteria within the waste matrix.

Consideration of the manner in which the pollutants were loaded (three separate layers) gives further credence to this argument as the loading technique used would tend to, at least initially, provide three localized pockets of higher pollutant concentrations (near each loading layer), separated by volumes of refuse with lower priority pollutant concentrations. Migration of the priority pollutants via leachate would be required for the initially uncontaminated zones of refuse to be affected by the pollutant loadings.

Originating from the refuse and added metal sludges, significant levels of sulfate were measured in the leachates of all ten columns as illustrated in Figures 49 and 50. Under the anaerobic reducing conditions which predominated after the initiation of active methane fermentation between approximately Days 700 and 800, sulfates were reduced to sulfides thus providing a potent precipitating agent for heavy metals present within the leachate. Confirming these reducing conditions were the consistently negative leachate oxidation-reduction potentials measured during active methanogenesis (Figures

Figure 49 Leachate Sulfate Concentrations,
Recycle Columns

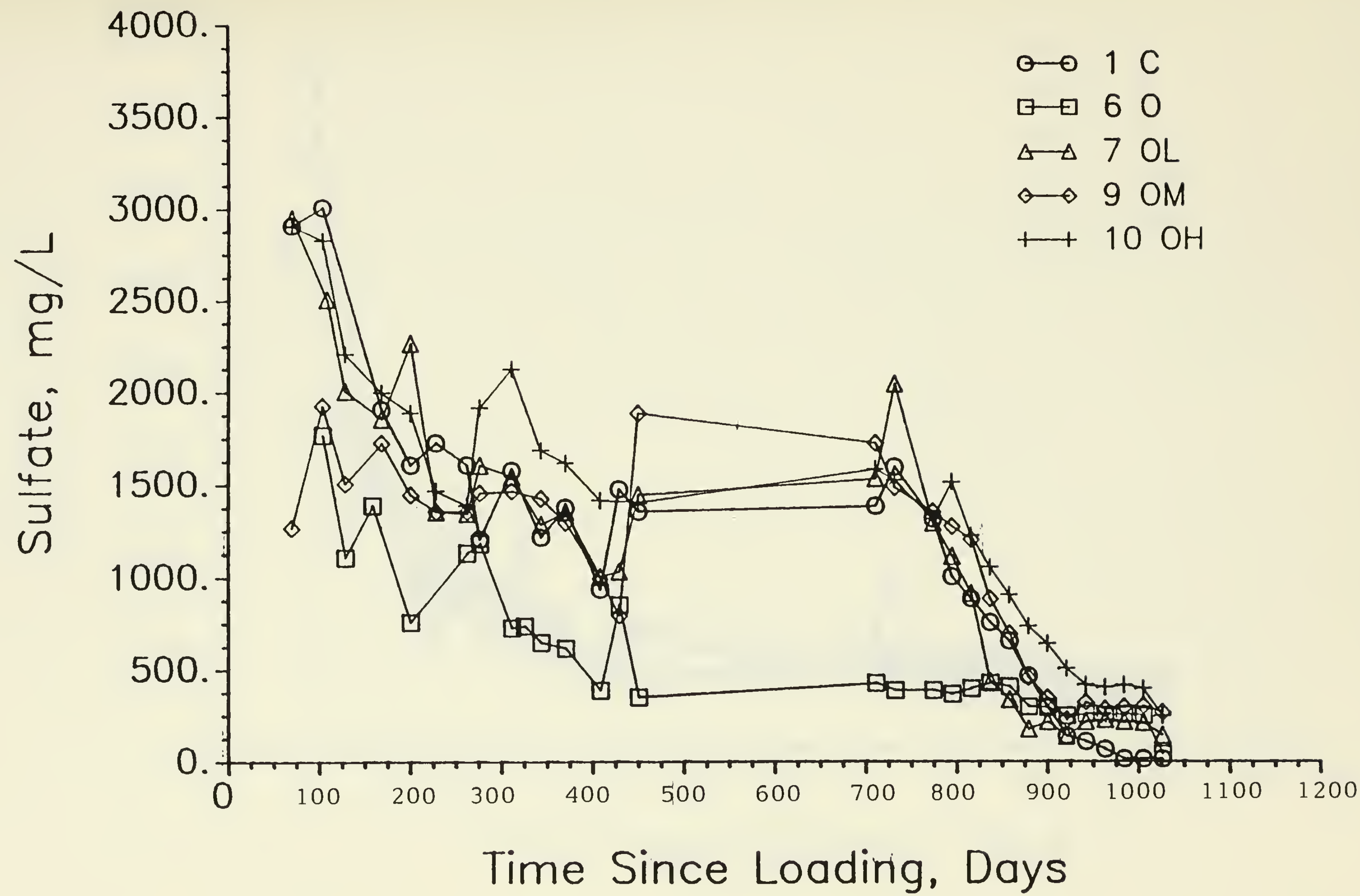
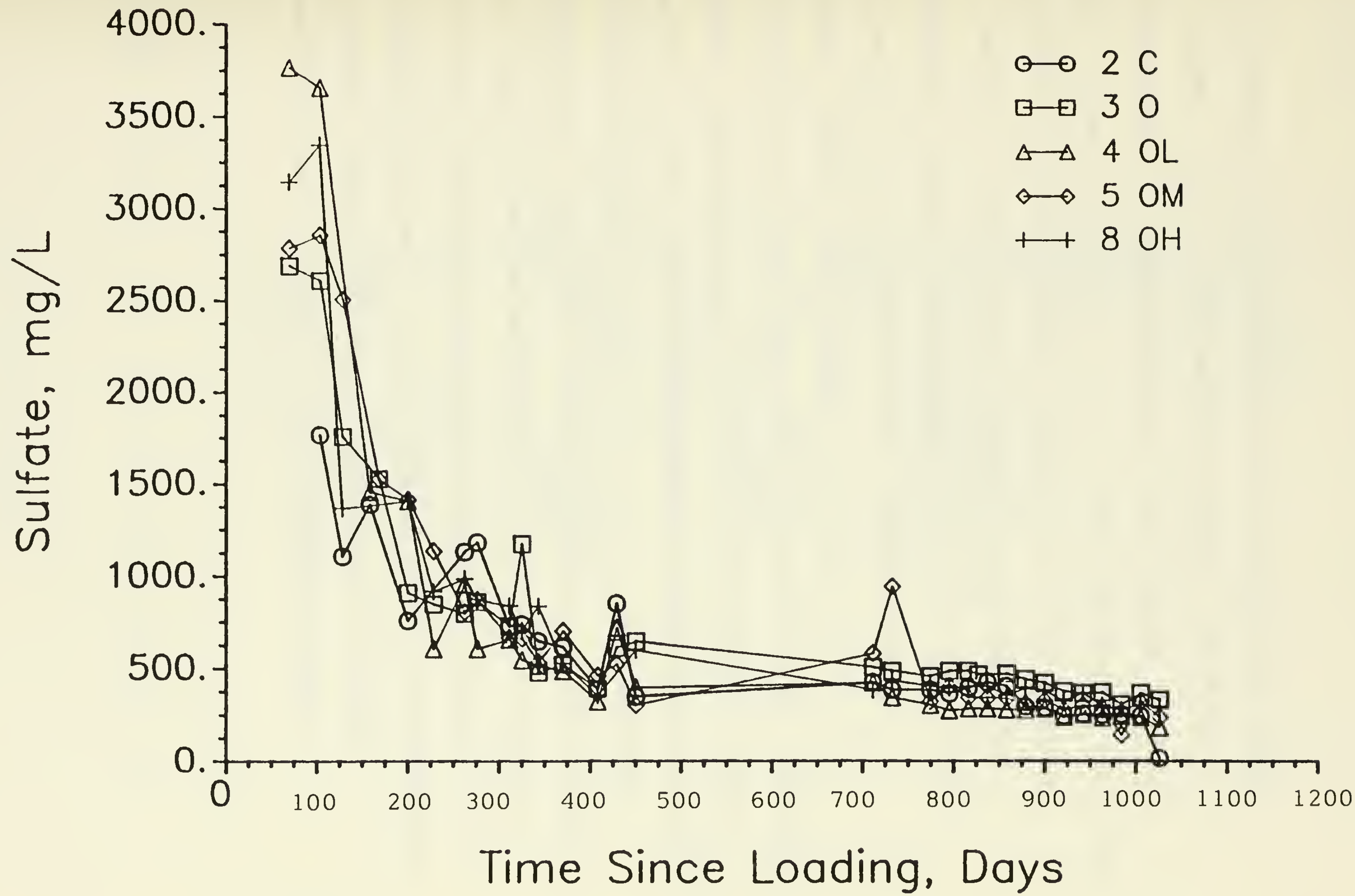


Figure 50 Leachate Sulfate Concentrations, Single Pass Columns



51 and 52).

While leachate sulfate concentrations within the single pass columns show the influence of washout, sulfate concentrations in the leachates of the recycle columns showed a significant decrease at a time coinciding with the initiation of active methane production. This suggests that leachate sulfates were reduced to sulfides which subsequently promoted the in situ precipitation of those heavy metals which form sparingly soluble sulfides (mercury, cadmium, lead, nickel, zinc and iron). The precipitation of these heavy metals and filtration from the leachate, especially as enhanced through leachate recycle, appeared to have lowered soluble metal concentrations below some toxic threshold concentration above which methane production was inhibited. An approximation of the ranges in which these thresholds may fall are contained in Table 17 which lists the average residual leachate concentrations of the spiked heavy metals for analyses performed between Days 700 and 800, the period during which active methane fermentation was initiated in the recycle columns.

Figure 51 Leachate Oxidation-Reduction Potentials, Recycle Columns

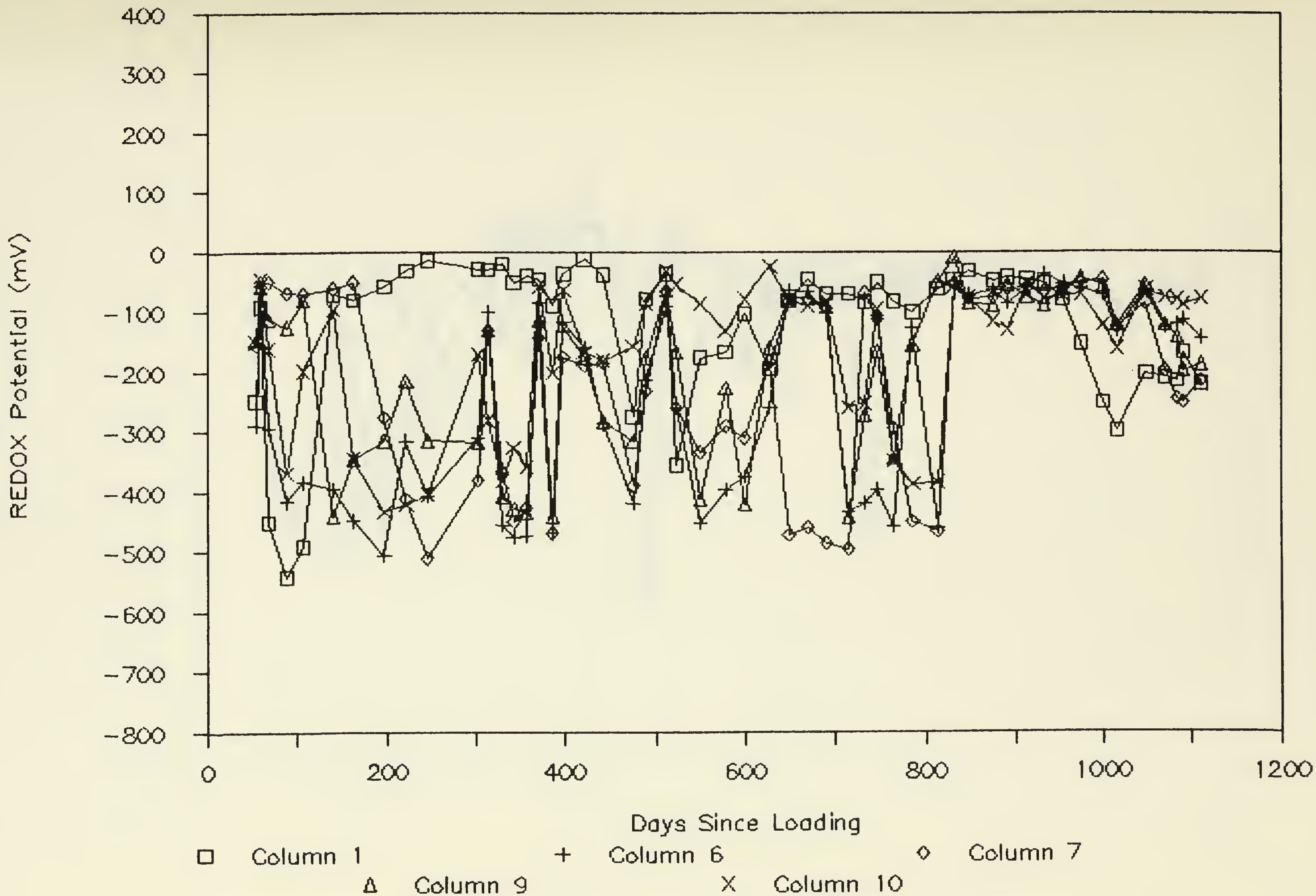


Figure 52 Leachate Oxidation-Reduction Potentials, Single Pass Columns

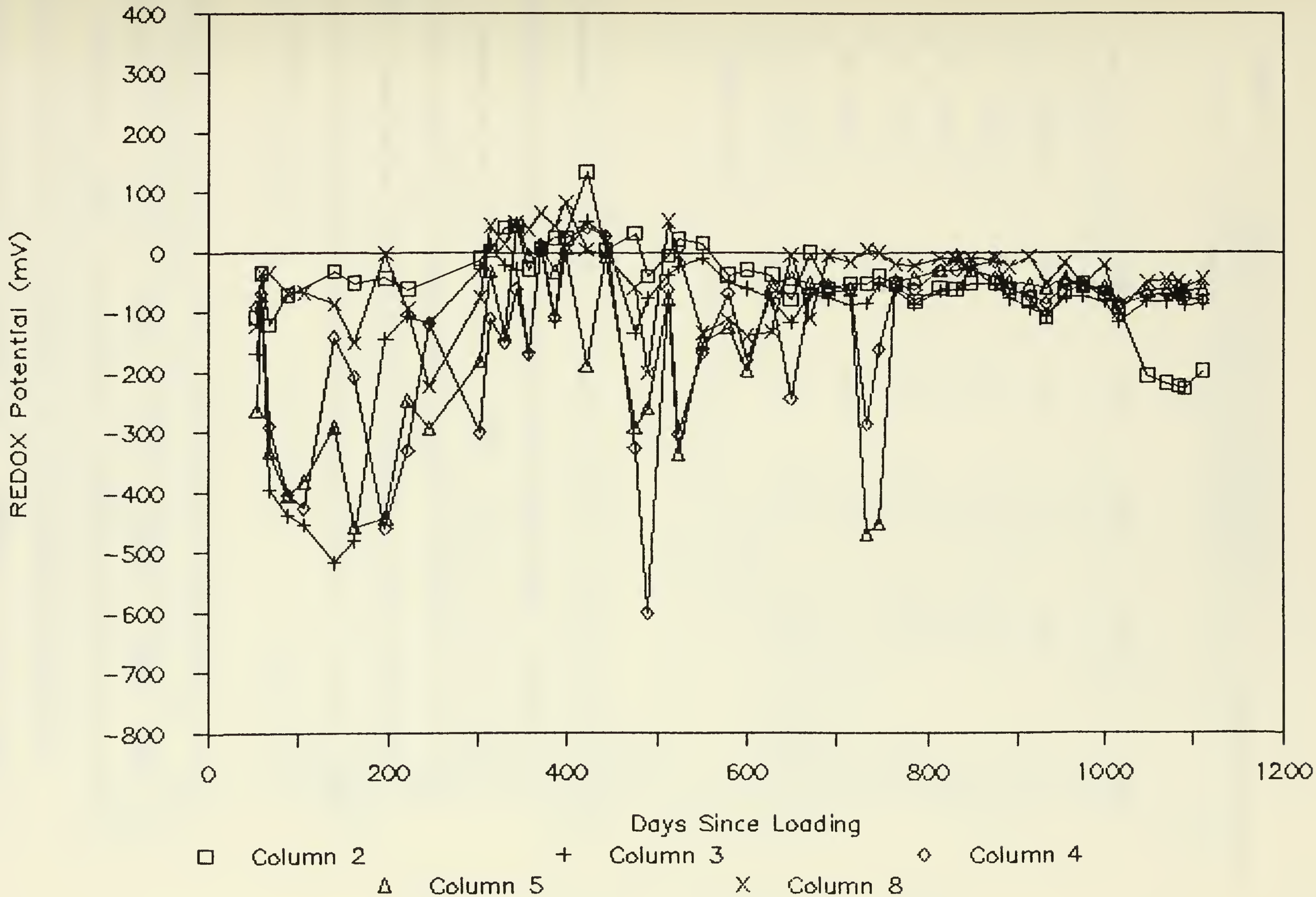


Table 17 Apparent Toxic Thresholds-
Average Residual Leachate Metal Concentrations between Days 700 and 800

Metal	1 (CR)	6 (OR)	7 (OLR)	9 (OMR)	10 (OHR)
Cd (mg/L)	0.0	0.0	1.3	8.8	21.8
Cr (mg/L)	0.0	0.0	0.0	0.0	0.0
Hg (ug/L)*	5.4	3.2	6.5	9.7	6.5
Ni (mg/L)	0.8	0.8	10.3	26.7	47.3
Pb (mg/L)	0.0	0.0	0.0	0.0	0.0
Zn (mg/L)	17.6	14.9	40.0	81.8	103.9

*Note units

Increases in leachate residual sulfide concentrations were observed in both the recycle and single pass control columns as well as Column 7 (OLR), which received the lowest amount of loaded heavy metals (Figures 53 and 54). This suggested that sulfides present in the remaining columns were forming sulfide precipitates at a rate equal to their production.

Generally consistent with the relative solubility of their respective sulfides (iron > zinc > nickel > lead > cadmium >> mercury) were the residual concentrations of these heavy metals within the leachates of the simulated landfill columns (Figures 55 through 66). However, in the case of

Figure 53 Leachate Sulfide Concentrations, Recycle Columns

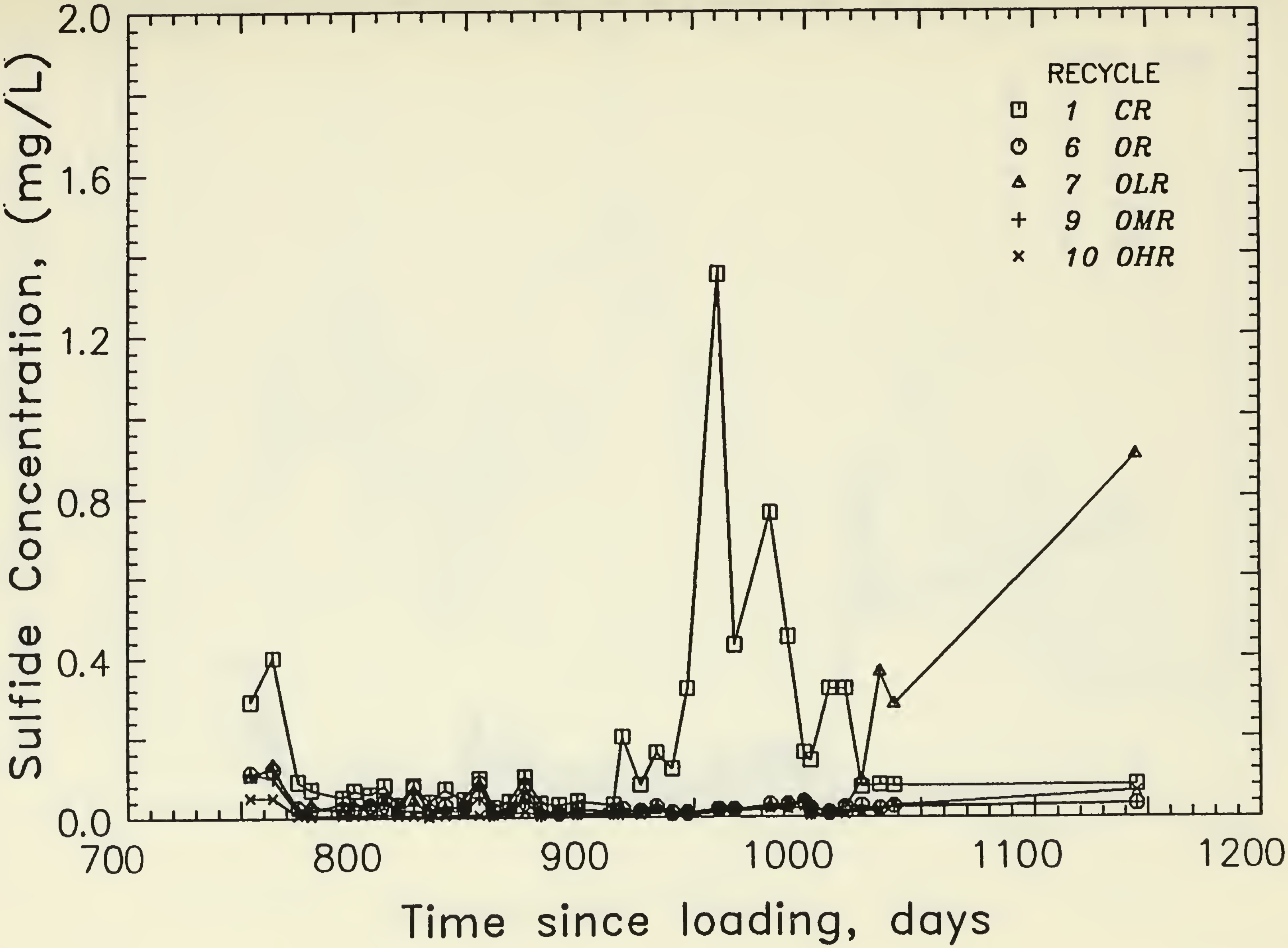


Figure 54 Leachate Sulfide Concentrations, Single Pass Columns

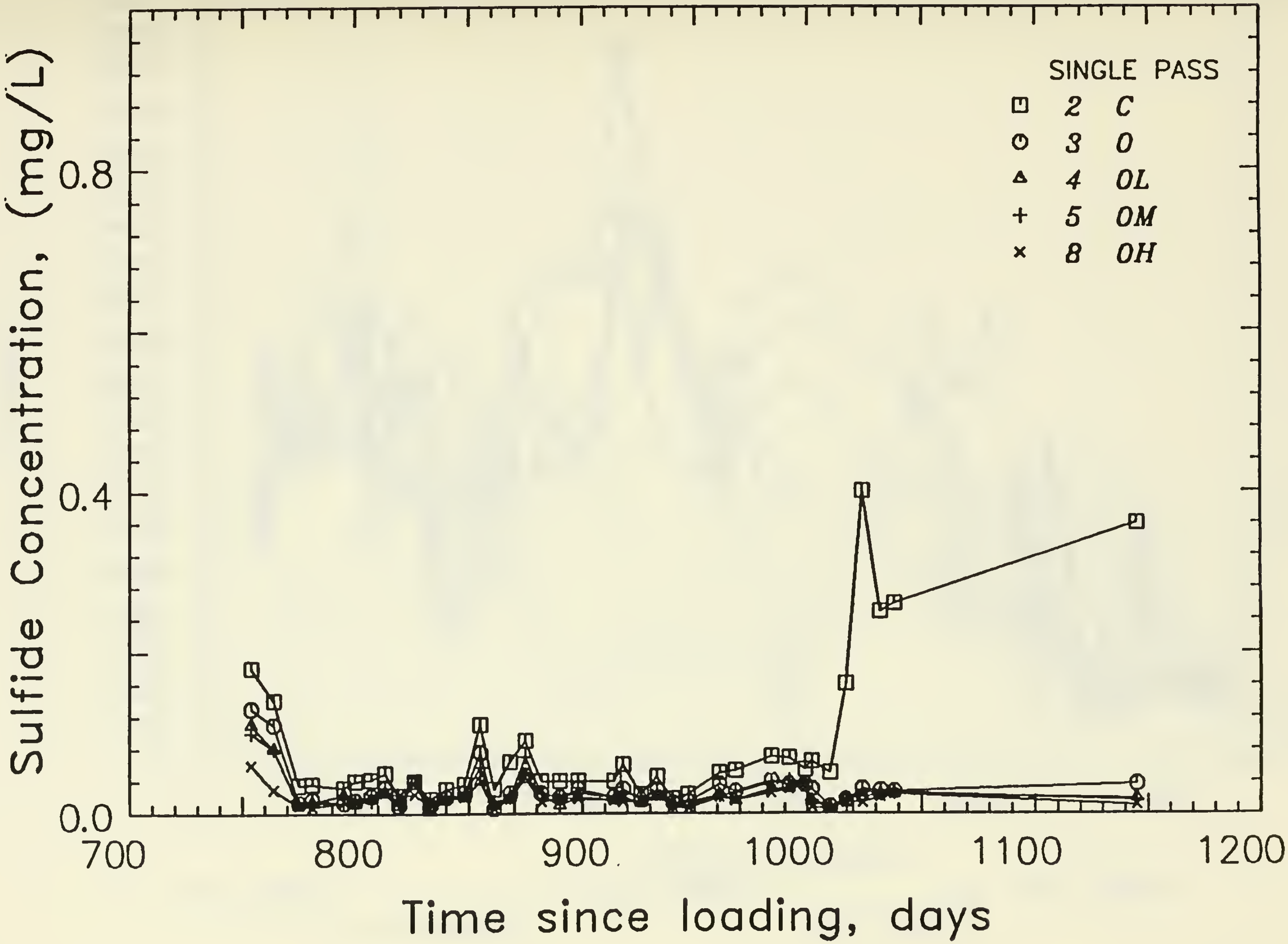


Figure 55 Leachate Iron Concentrations, Recycle Columns

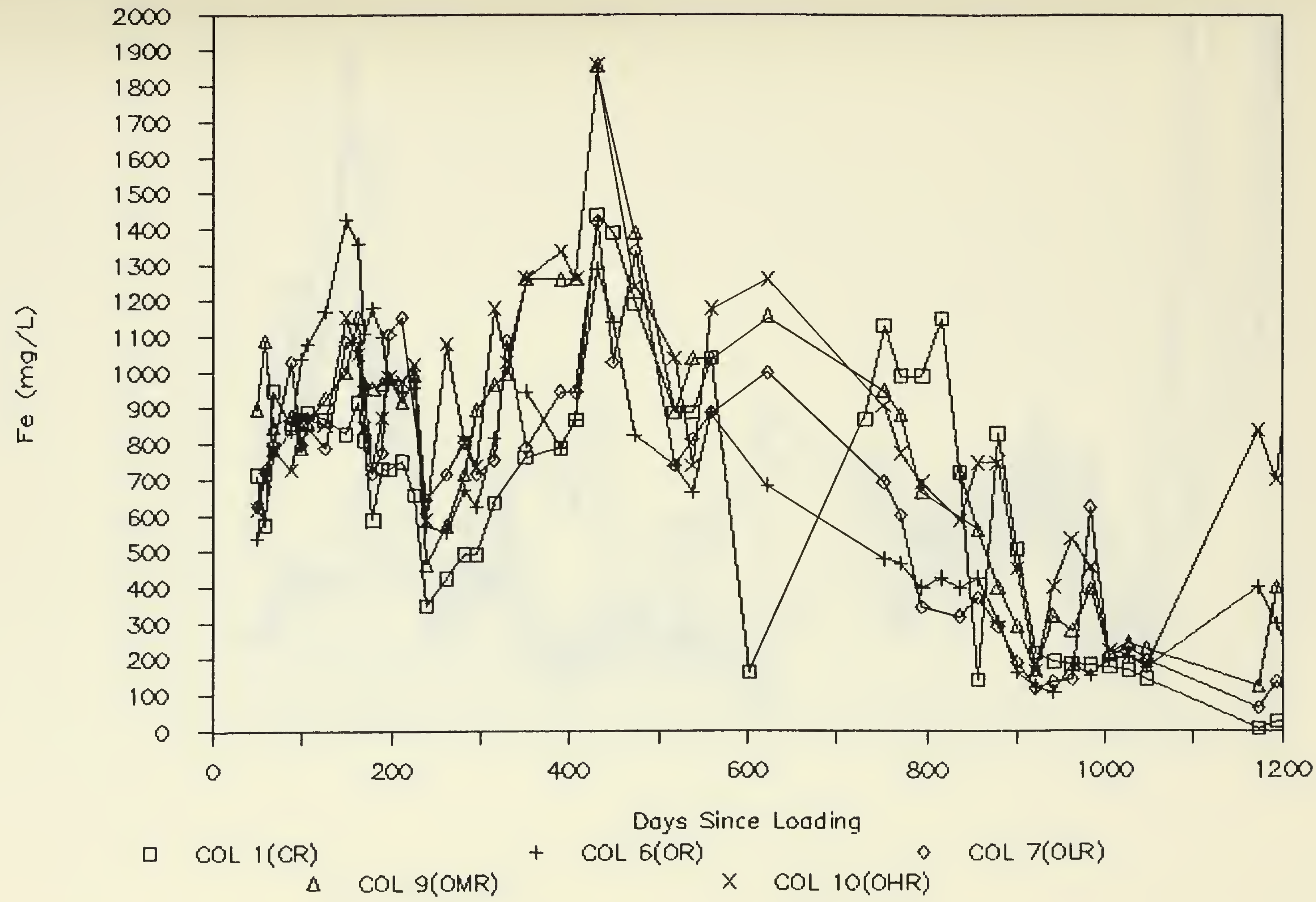


Figure 56 Leachate Iron Concentrations, Single Pass Columns

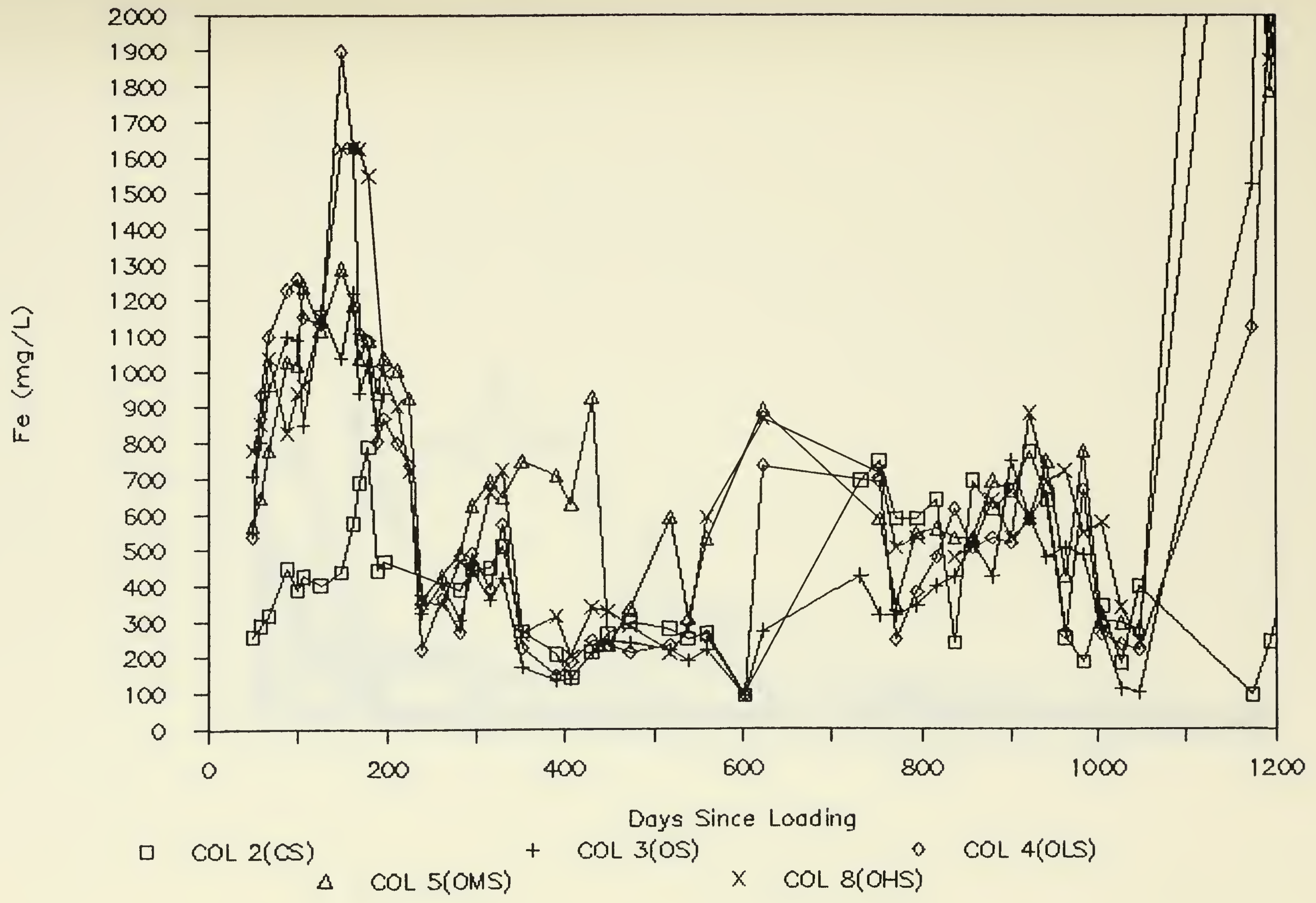


Figure 57 Leachate Zinc Concentrations, Recycle Columns

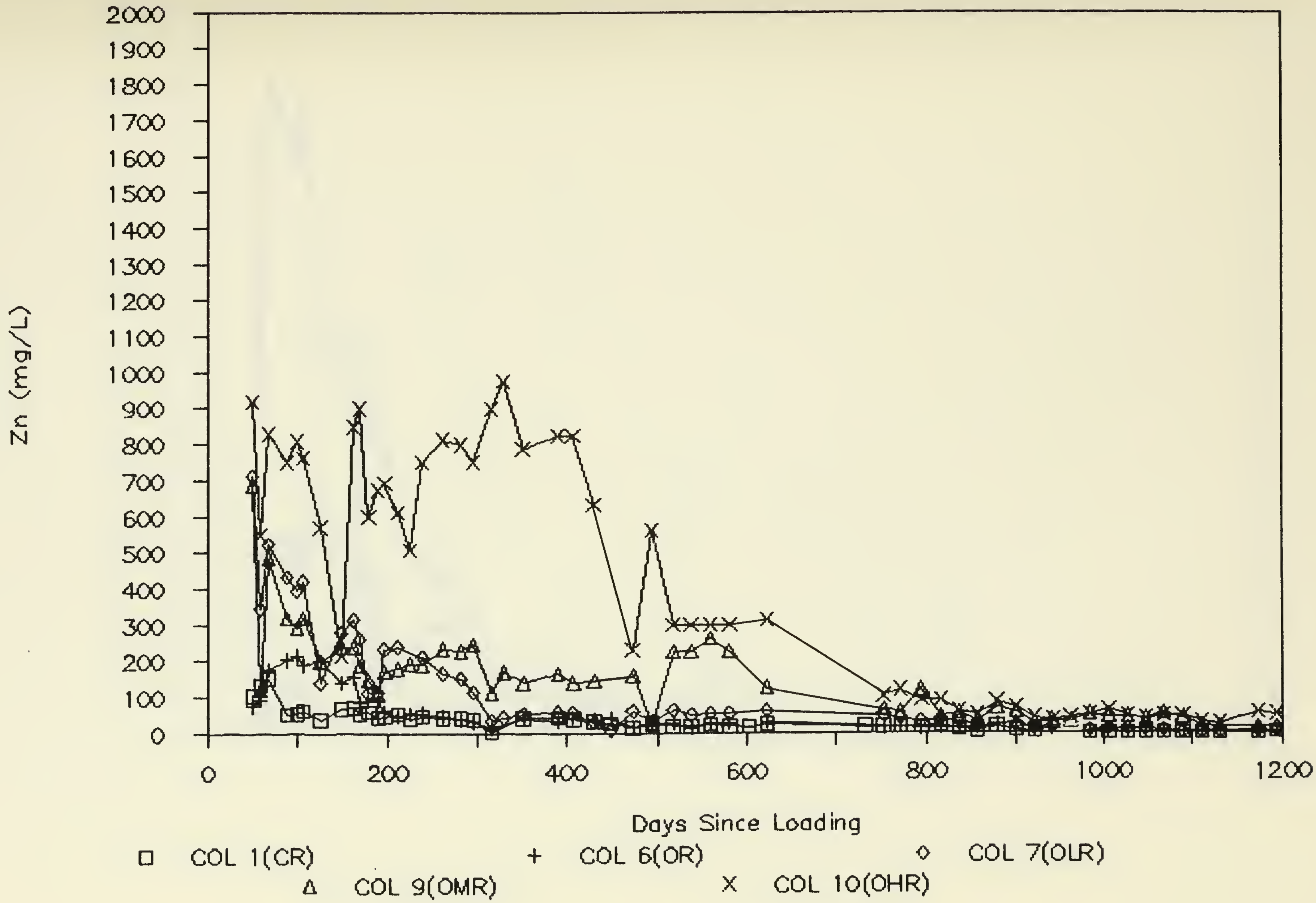


Figure 58 Leachate Zinc Concentrations, Single Pass Columns

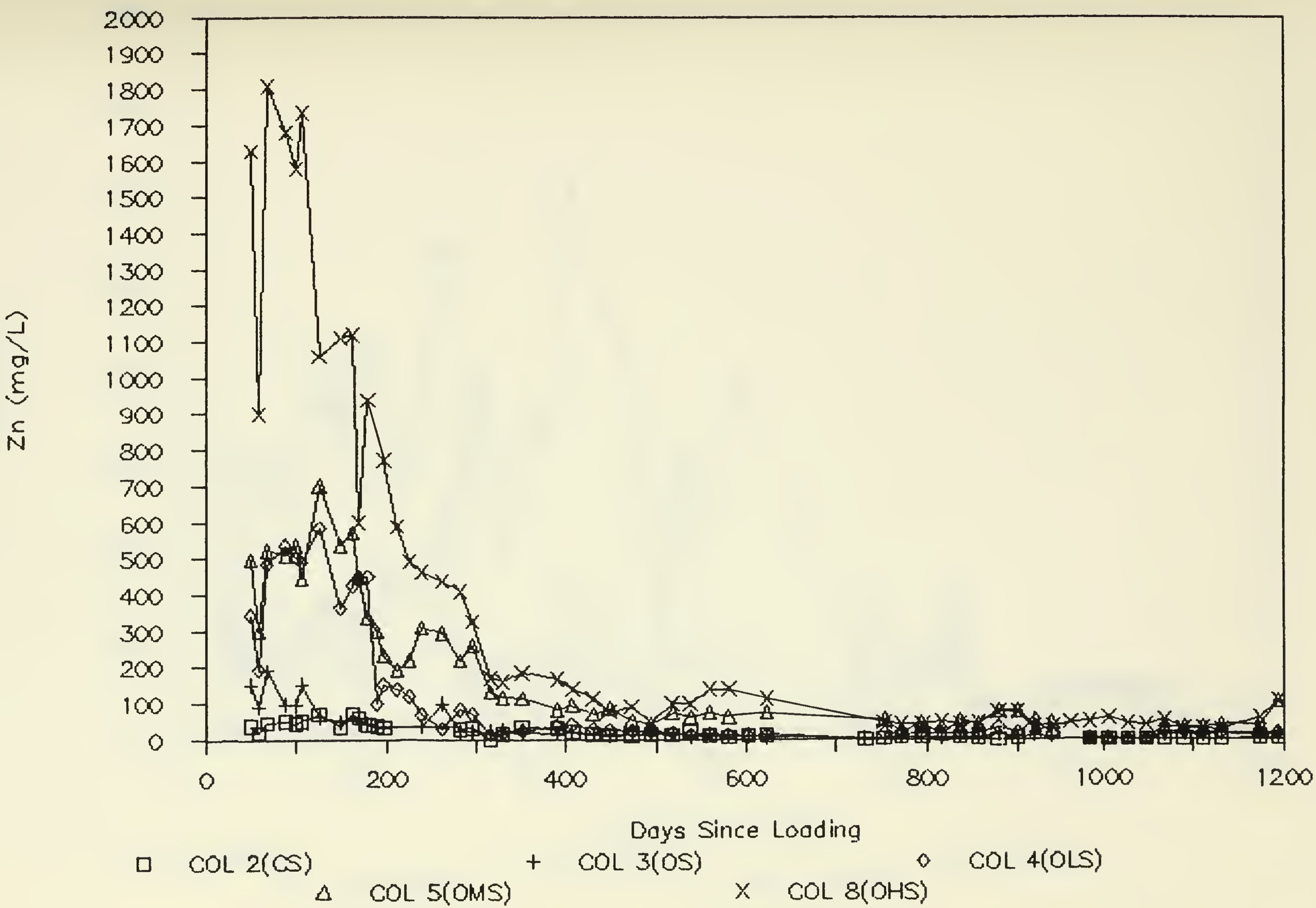


Figure 59 Leachate Nickel Concentrations, Recycle Columns

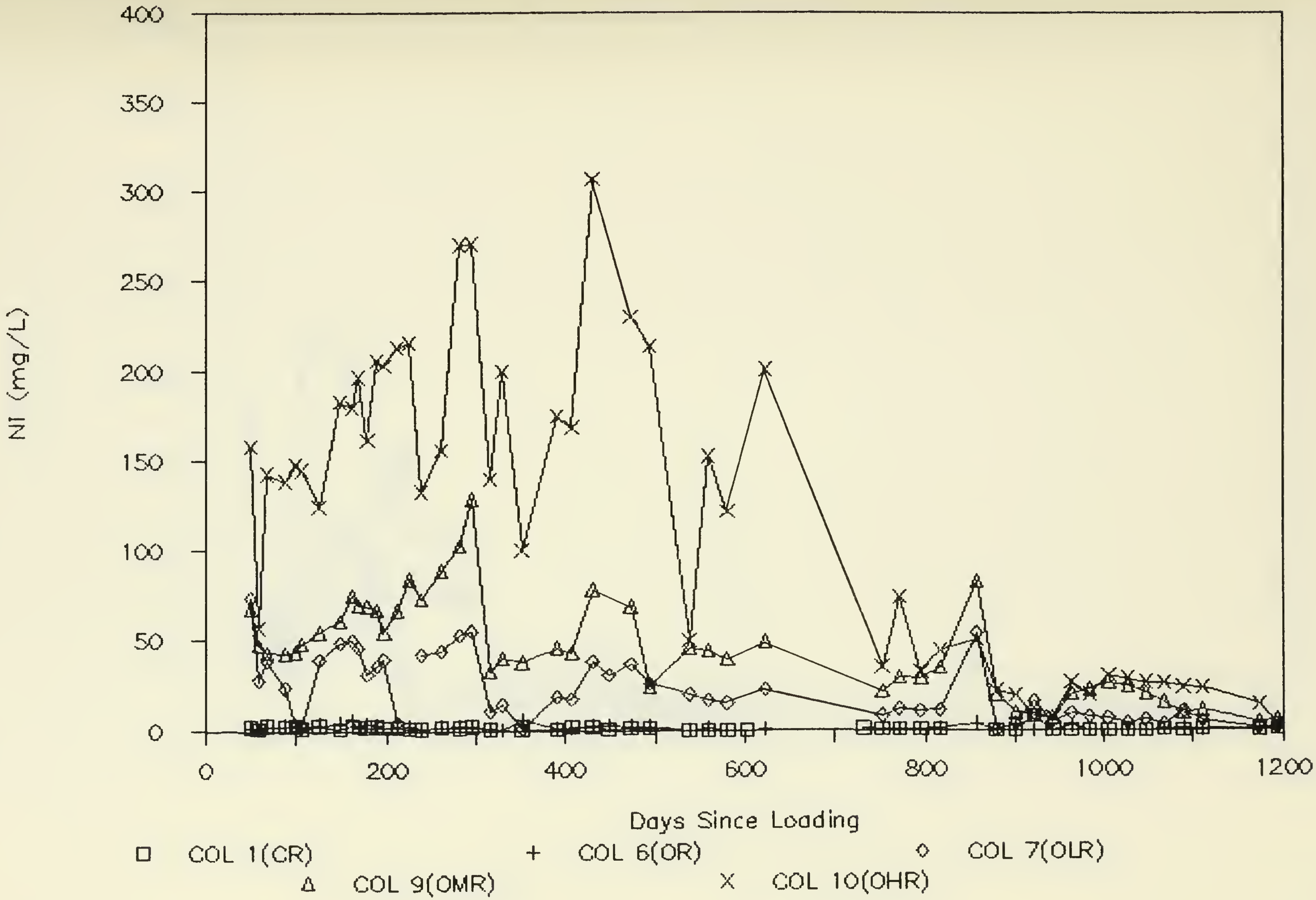


Figure 60 Leachate Nickel Concentrations, Single Pass Columns

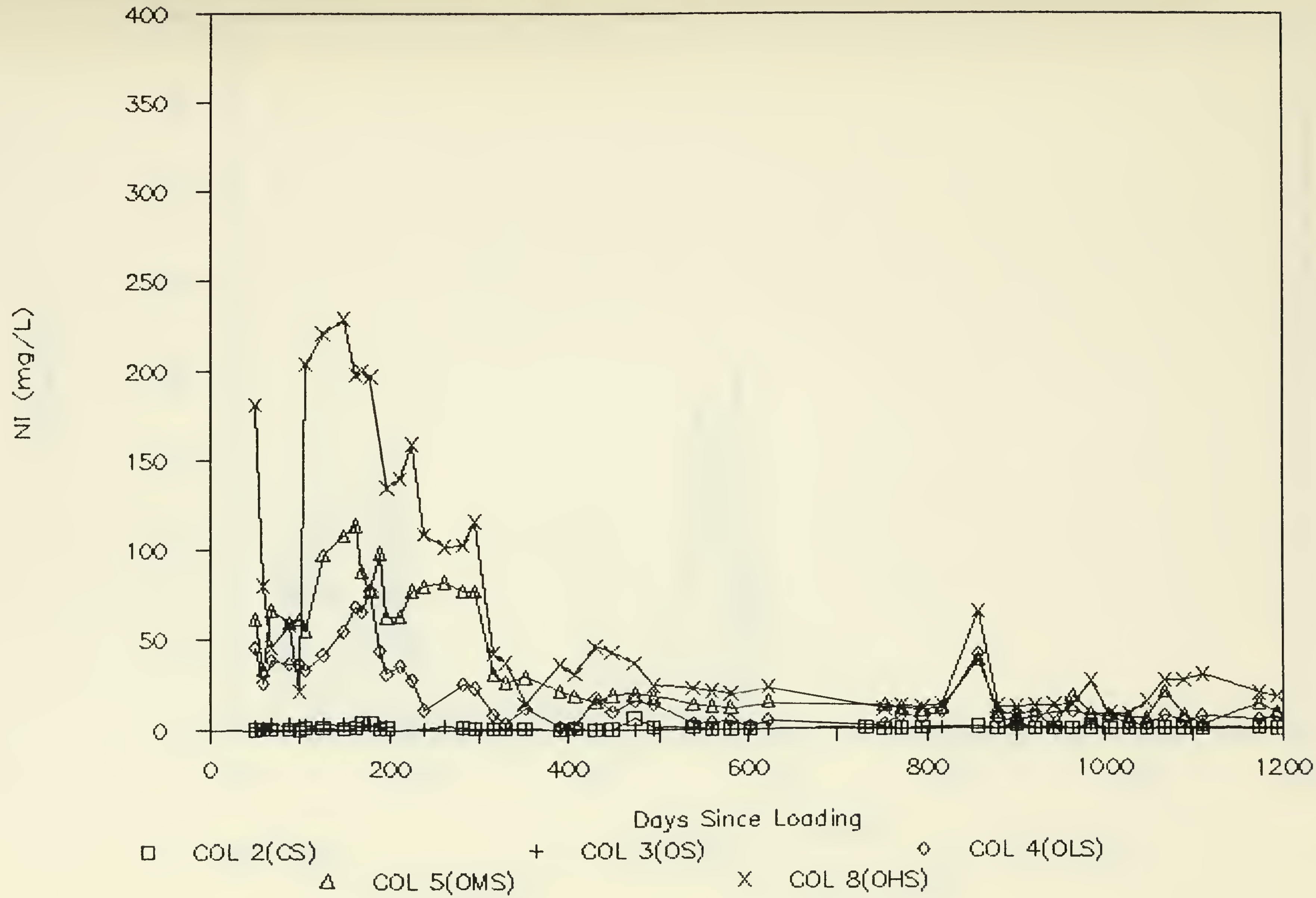


Figure 61 Leachate Lead Concentrations, Recycle Columns

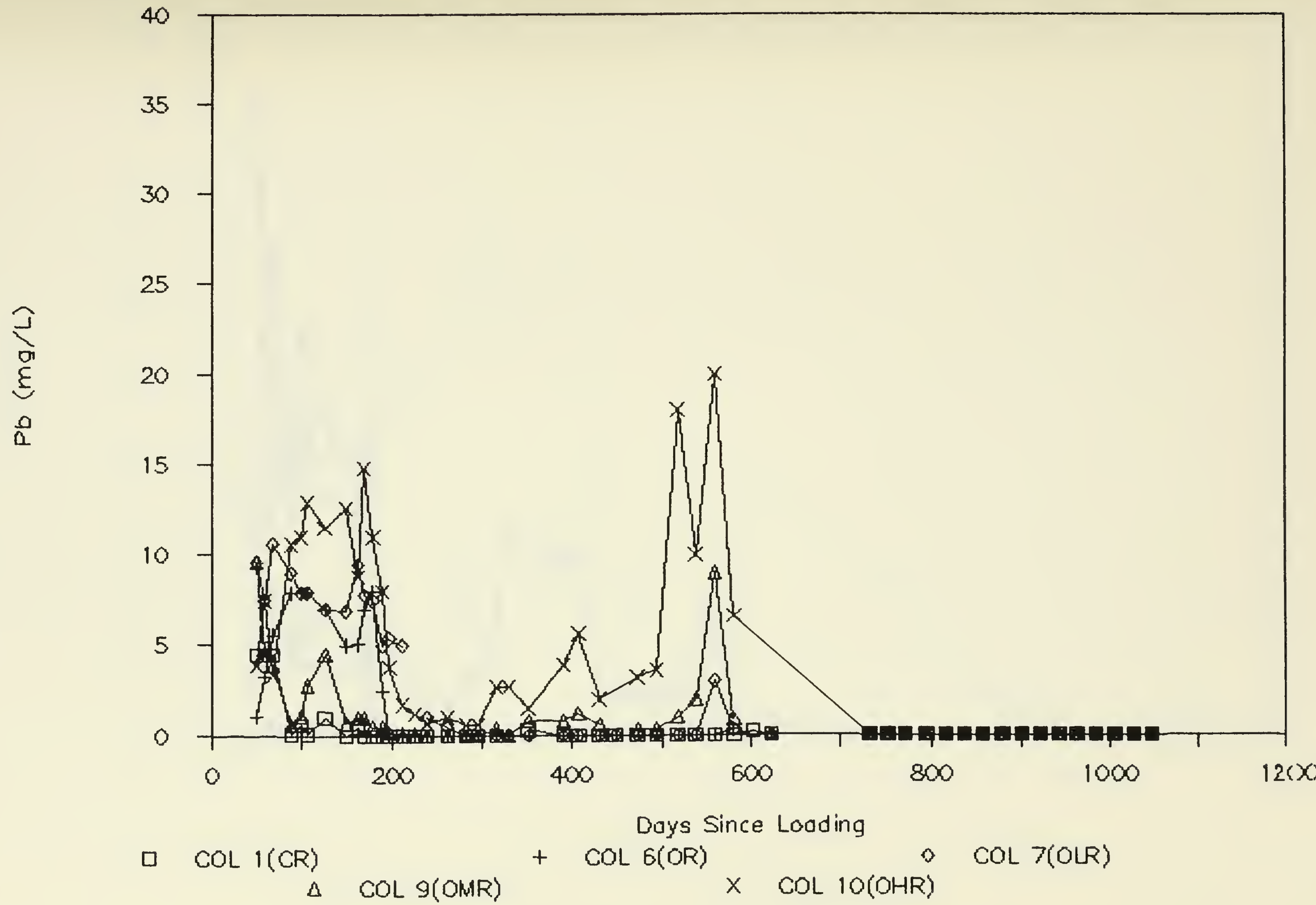


Figure 62 Leachate Lead Concentrations, Single Pass Columns

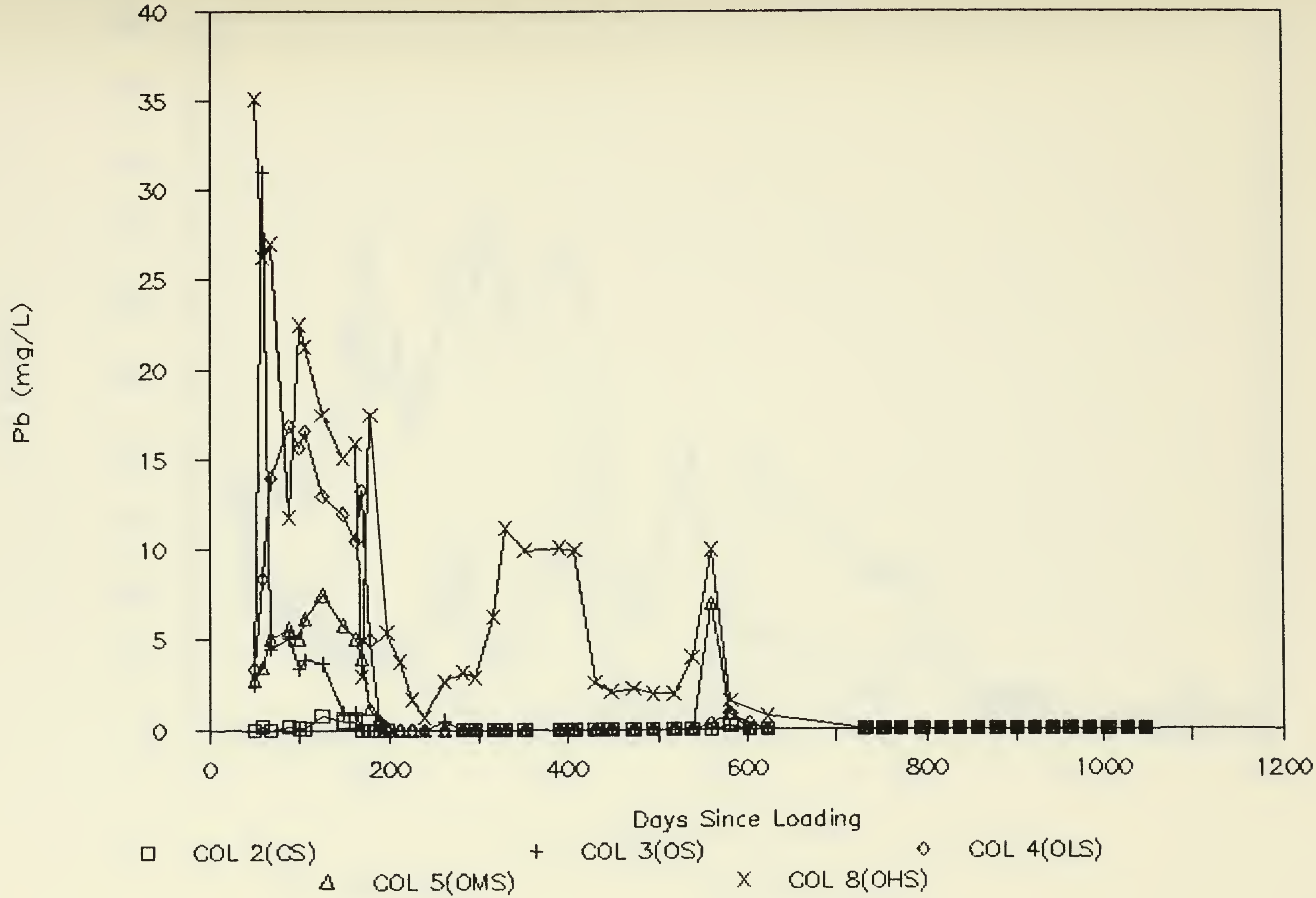


Figure 63 Leachate Cadmium Concentrations, Recycle Columns

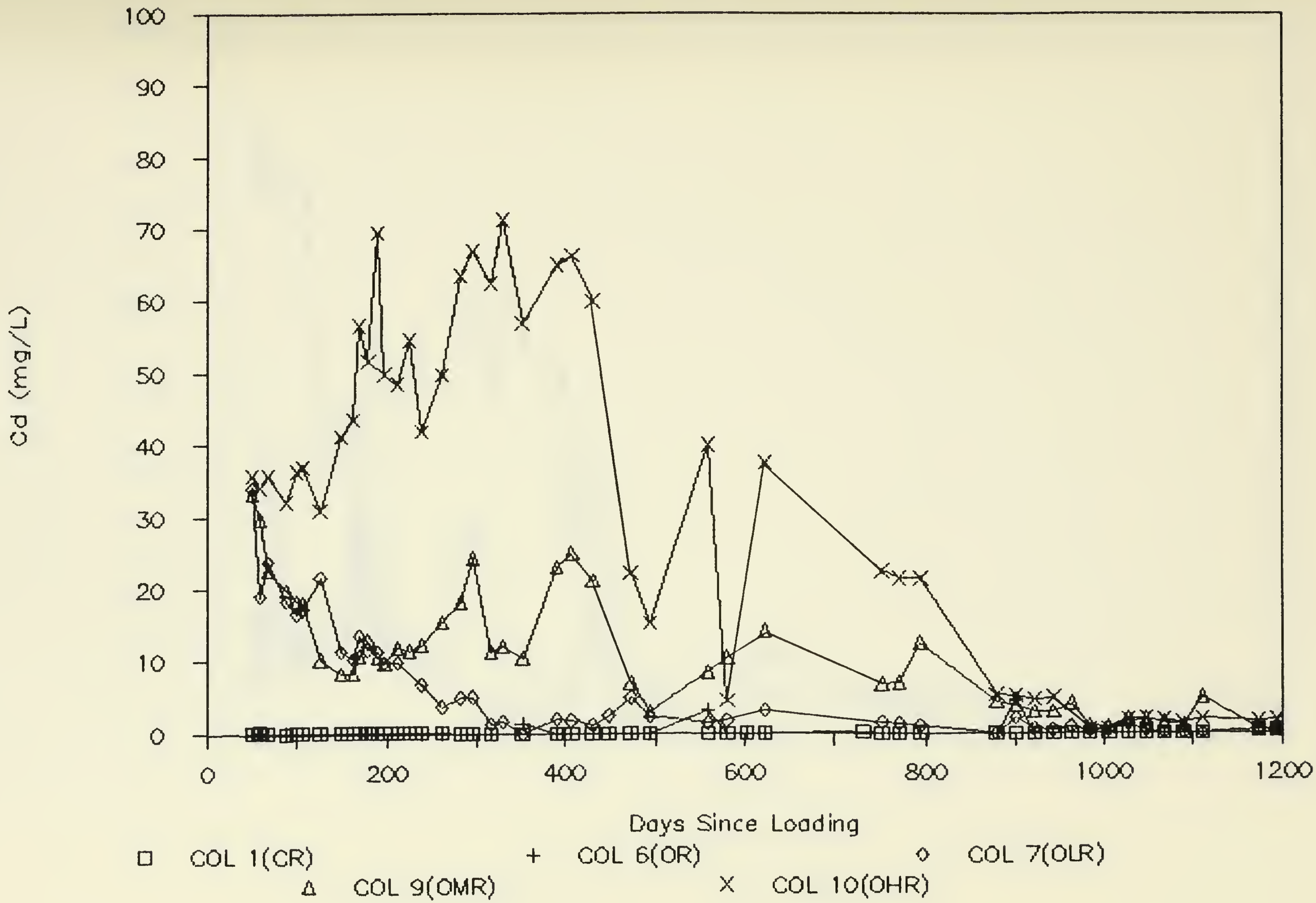


Figure 64 Leachate Cadmium Concentrations, Single Pass Columns

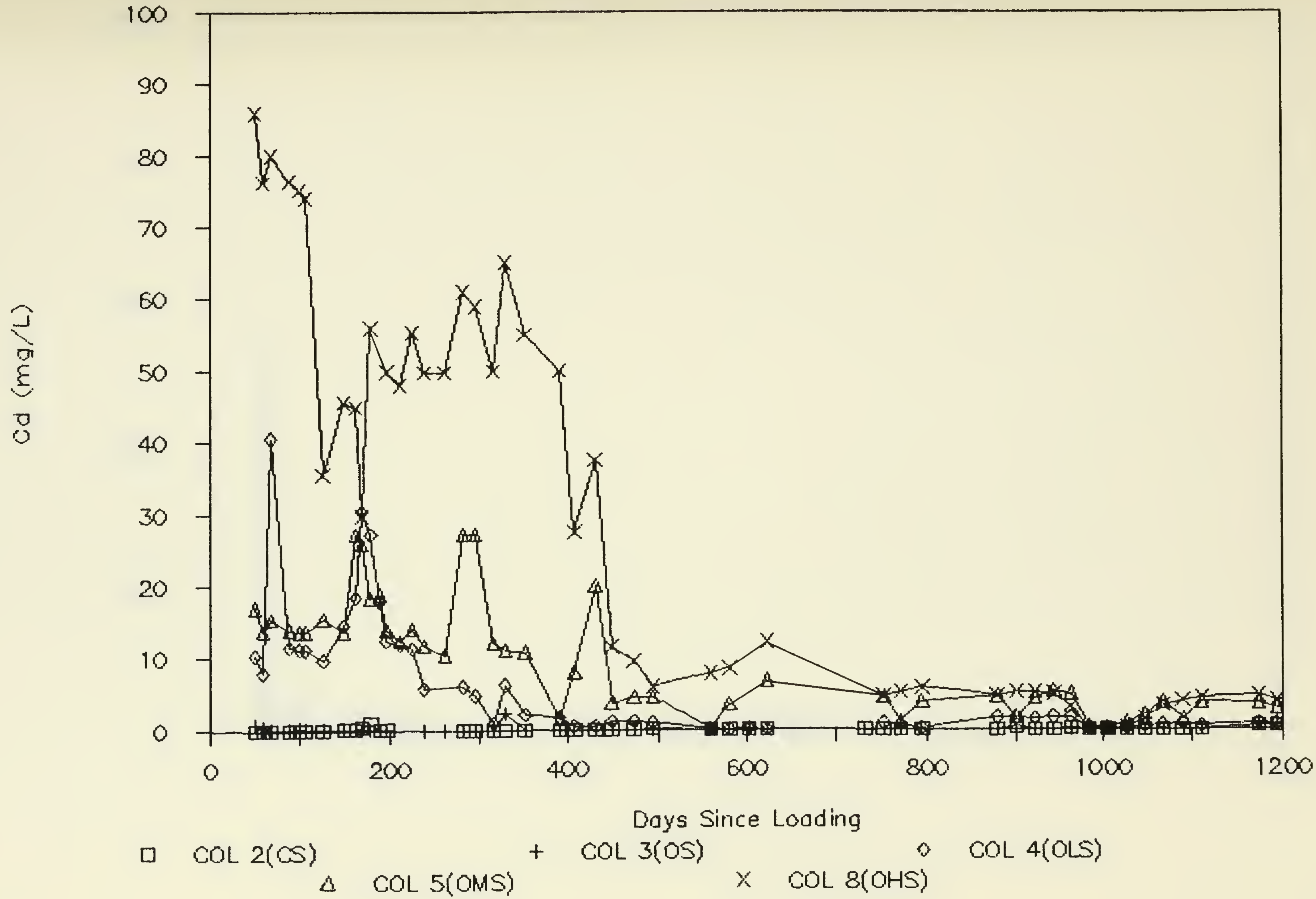


Figure 65 Leachate Mercury Concentrations, Recycle Columns

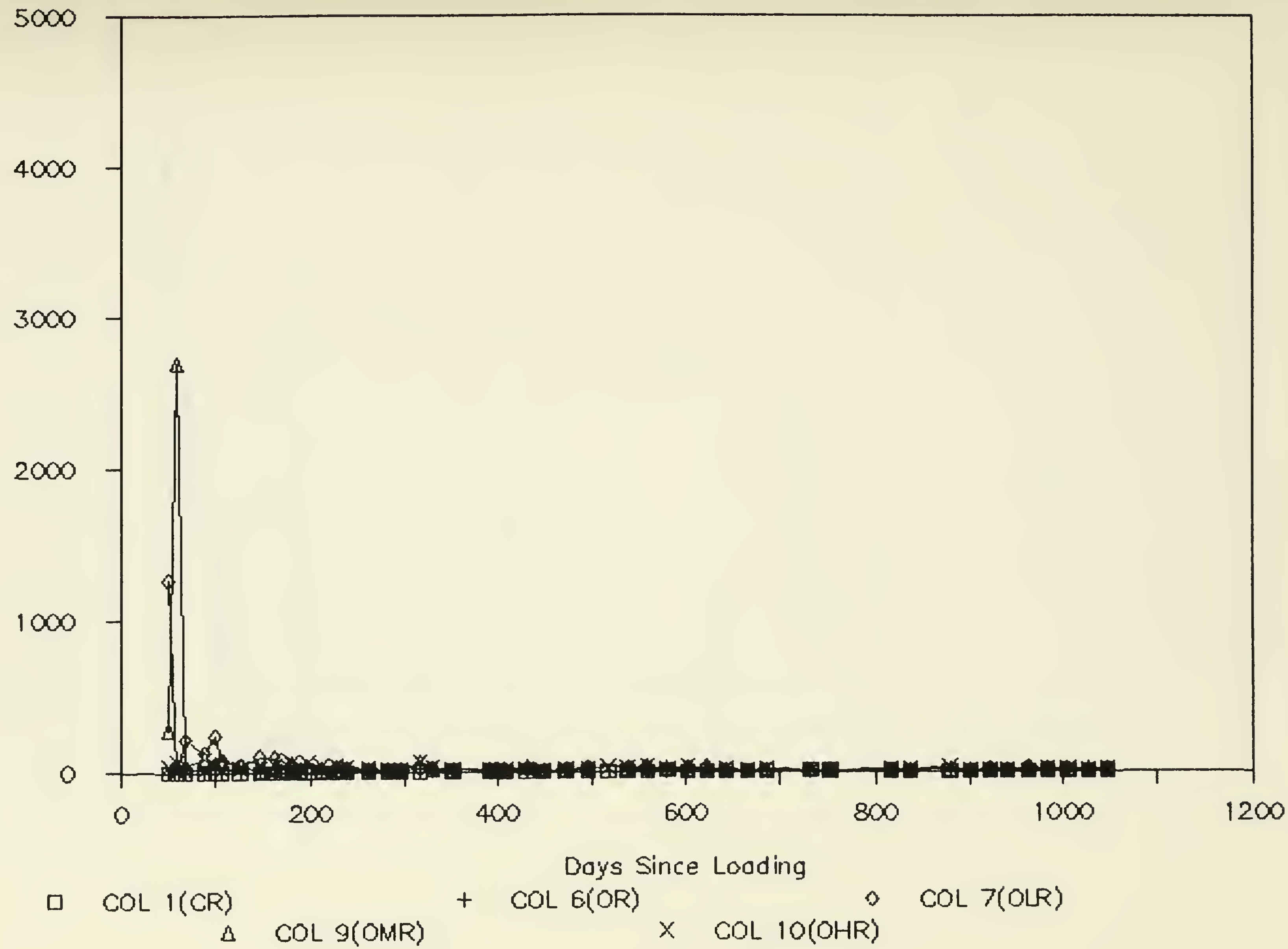
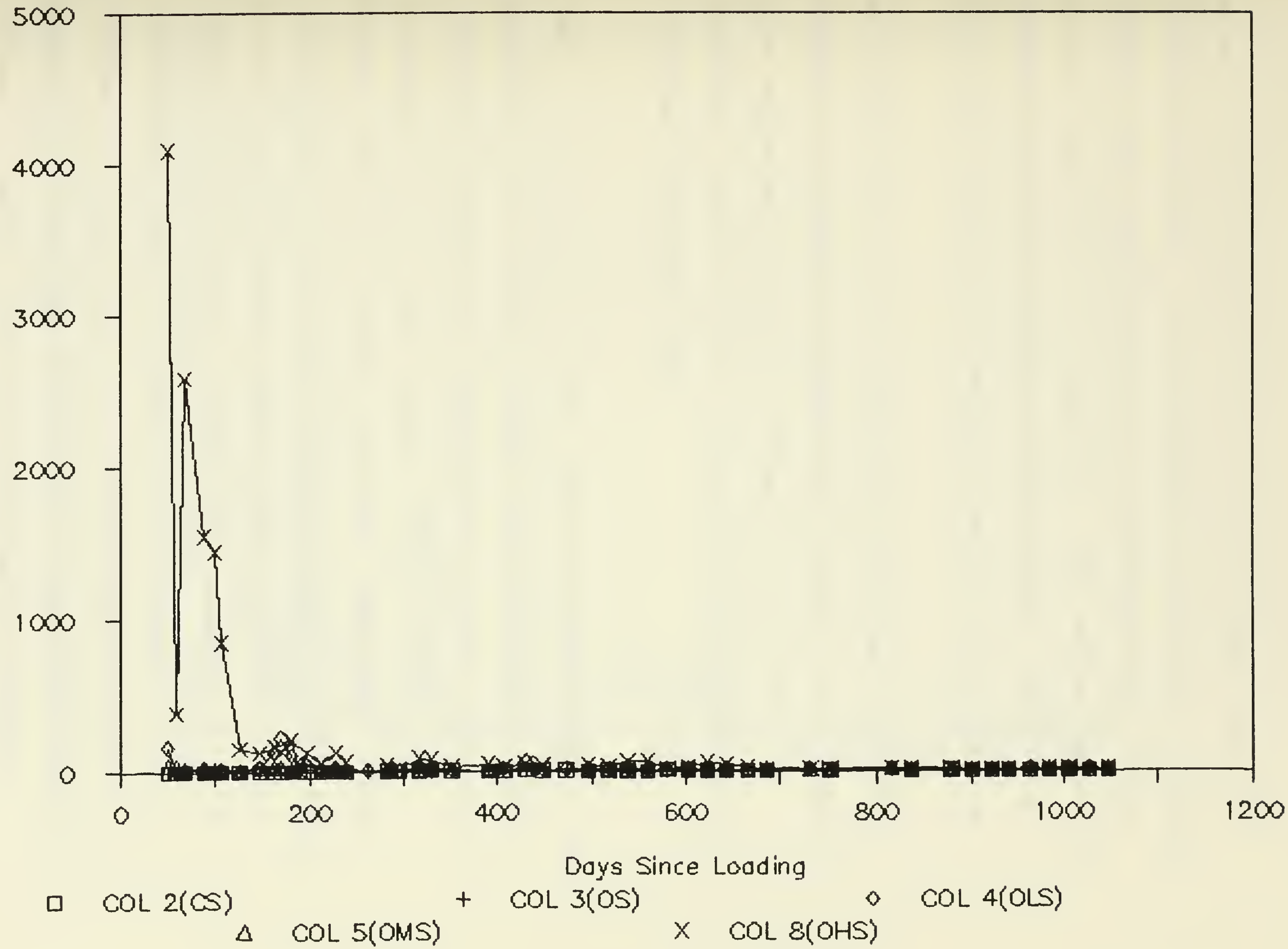


Figure 66 Leachate Mercury Concentrations, Single Pass Columns



mercury, its detection at the part per billion level (Figures 67 and 68), in the presence of available sulfides, suggests that precipitation of its sulfide (pK_{so} = 50.0) was not controlling its solubility. But rather, under the reducing conditions present in the columns, it is more likely that reduction to metallic mercury was occurring.

Controlled likely by its hydroxide precipitate ($Cr(OH)_3$), chromium was generally undetectable in any of the leachates after approximately Day 550 (Figures 69 and 70). (Analytical results for all the above mentioned metals are contained in Appendix VIII.)

Common to the patterns of most metal concentrations in the leachates of the recycle columns were perturbations which continued throughout the experimental period, especially in the cases of iron, zinc, nickel, cadmium and mercury. Although there is no direct basis for comparison, likely contributing to this noted variability was the application of the priority pollutant metal sludge mixtures to the refuse in three discrete layers. The presence of three concentrated layers of these pollutants seems to have provided the opportunity for variably-timed releases of the metals as more complete saturation of the refuse mass was achieved. However, the mixing afforded by repeated leachate recycle and the attenuation mechanisms described previously were most likely accountable for the dampening

Figure 68 Leachate Mercury Concentrations, Single Pass Columns
(expanded scale)

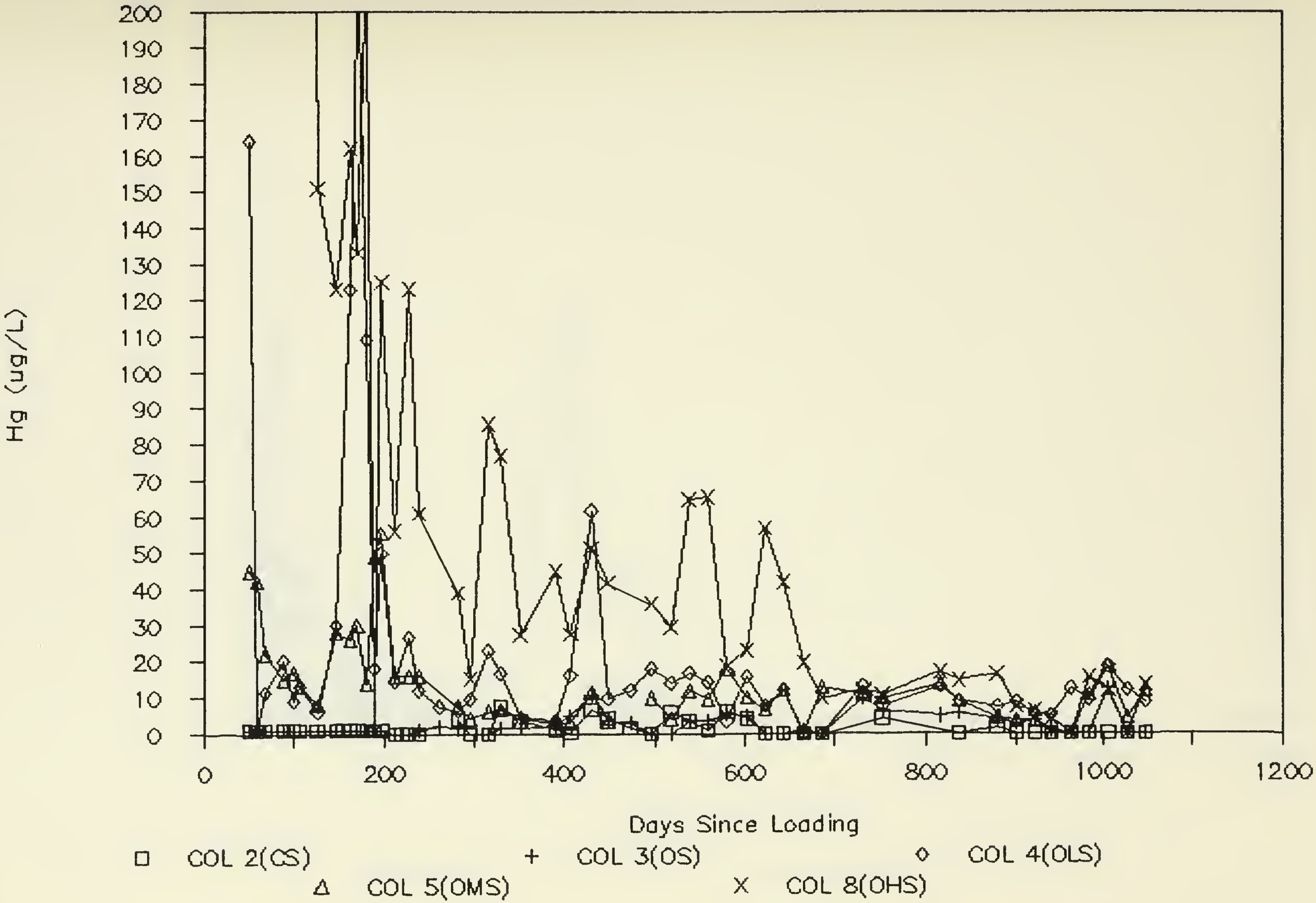


Figure 69 Leachate Chromium Concentrations, Recycle Columns

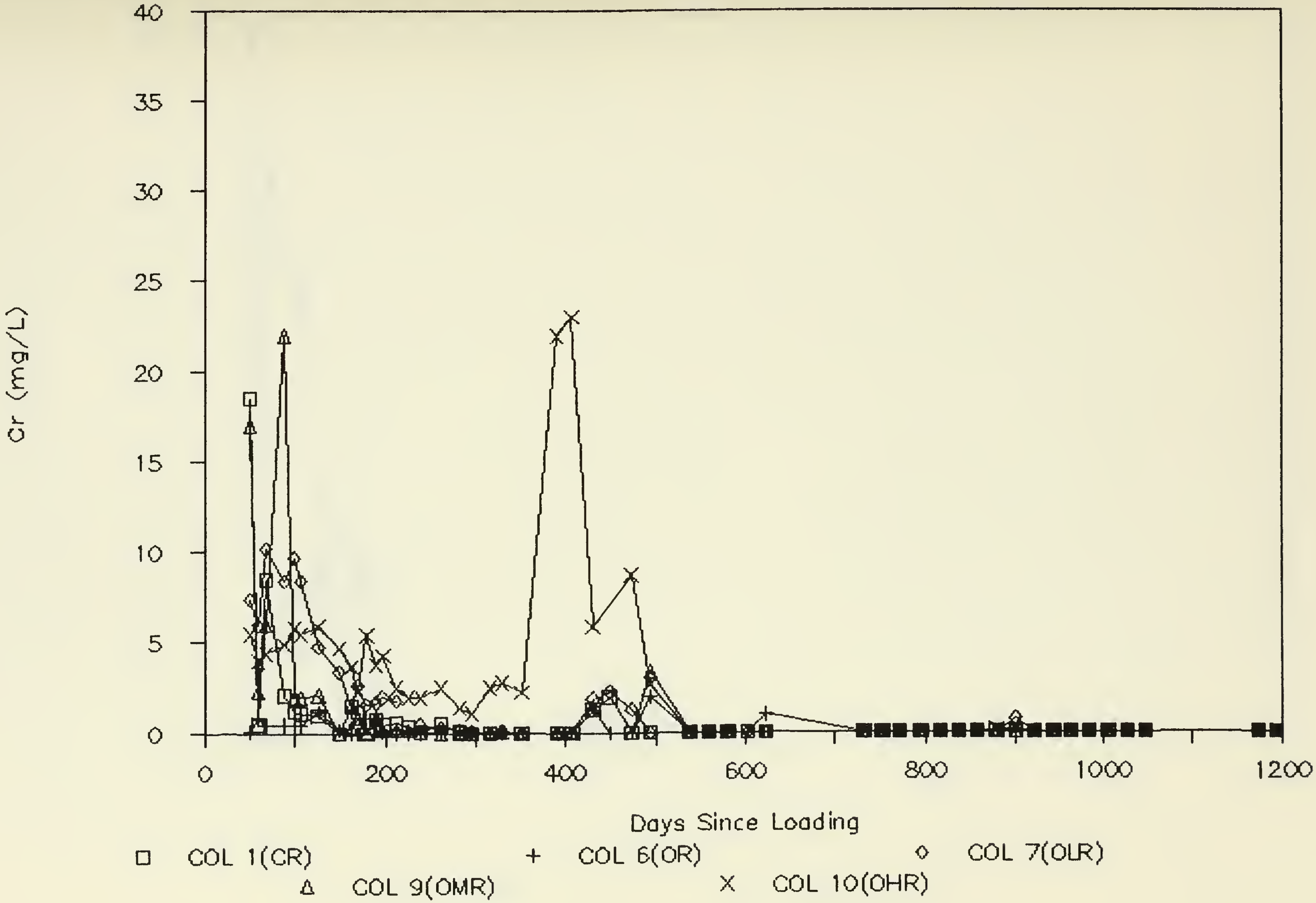
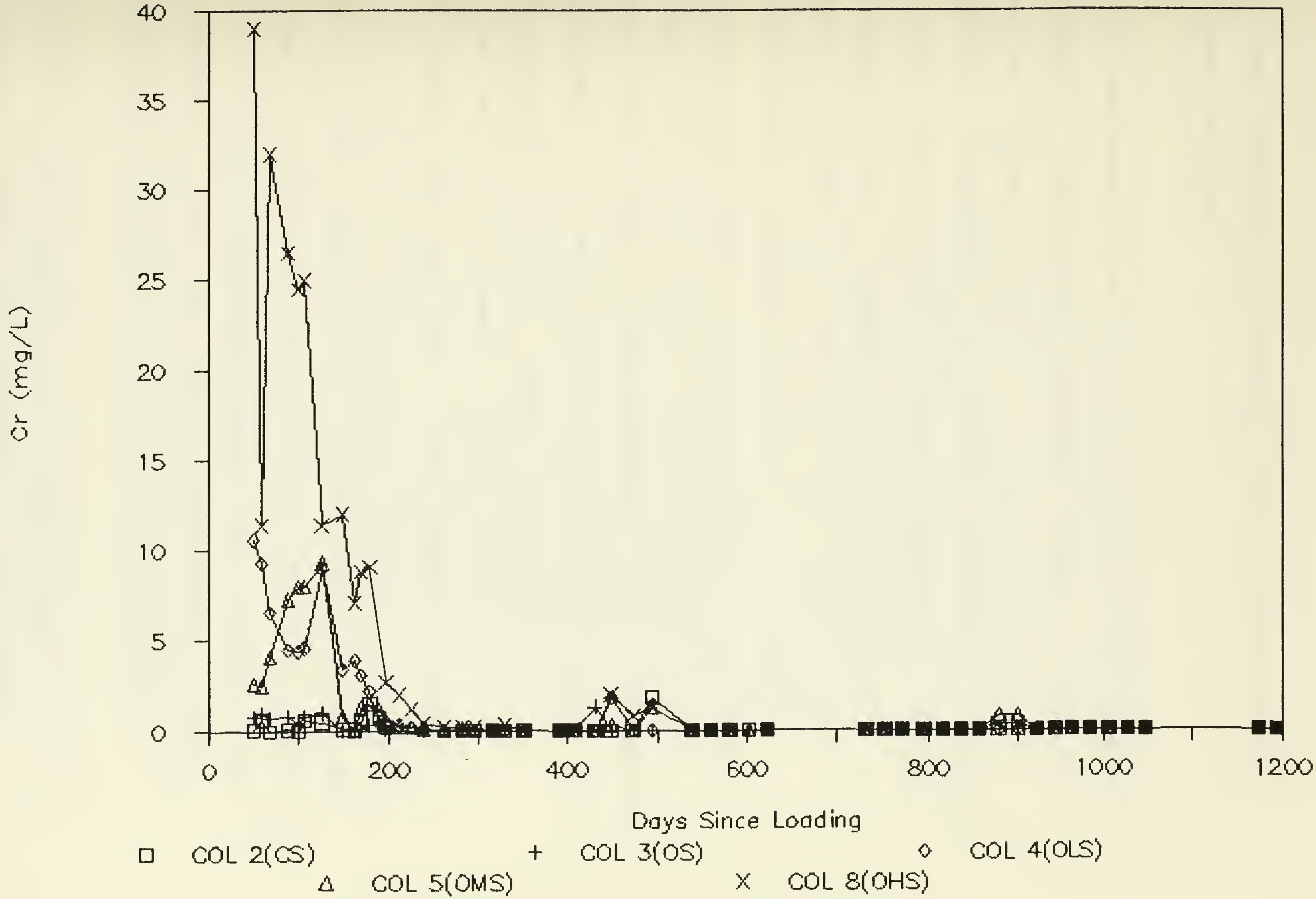


Figure 70 Leachate Chromium Concentrations, Single Pass Columns



of these variations in concentrations as operation of the columns continued.

As is the general case with microbially-mediated treatment processes, fluctuations in inhibitor levels, as well as absolute concentrations, can influence the degree of toxicity. Therefore, in the present experiment, it would at first appear that had the metal sludges been loaded by thoroughly mixing throughout the refuse mass, less variability might have occurred in the leachate metal concentrations, thereby reducing the toxic effects. However, due to such a uniform application of the metal sludge, metal mobilization, especially during the acid phase, would likely be enhanced because of the much greater opportunity for contact with an aggressive leachate. With increased metal mobility, higher leachate metal concentrations would result, thereby creating an environment even more toxic to the requisite microbial flora in spite of the fact that the concentrations would be less variable. Additionally, thorough mixing of the metal sludge with the refuse would eliminate the zone, or pocket, of initially uncontaminated refuse, which provides a local environment in which the initial establishment of large populations of viable microorganisms can take place.

Analysis of the leachates for the twelve organic priority pollutants provided some indication of the relative

mobility of these compounds under the simulated landfill conditions. Of the five non-polar organic compounds spiked in the test columns, only naphthalene showed any significant mobility (Figures 71 and 72). Lindane was only scarcely detected in Columns 4 (OLS), 5 (OMS), 6 (OR), 7 (OLR), 9 (OMR) and 10 (OHR), at levels at or below 20 parts per billion, and only after Day 963. The three other non-polar spiked organic compounds, hexachlorobenzene, dieldrin and dioctylphthalate were never detected in the leachates of any of the columns.

Dibromomethane and 1,1,2-trichloroethylene, the two purgeable volatile organics loaded, both appeared in the leachates early during the experimental period, and in relatively high concentrations (Figures 73 through 76) indicating high mobility of these pollutants. The two loaded extractable volatile organics, 1,4-dichlorobenzene and 1,2,4-trichlorobenzene, had comparatively low mobility as indicated in the slow elution of these compounds from the refuse, and relatively low concentrations in the leachates (Figures 77 through 80).

Leachate concentrations among the three polar, non-volatile organic priority pollutants loaded, nitrobenzene, 2-nitrophenol and 2,4-dichlorophenol, varied as a group. Figures 81 and 82 show the slow, yet distinct migration of

Figure 71 Leachate Naphthalene Concentrations, Recycle Columns

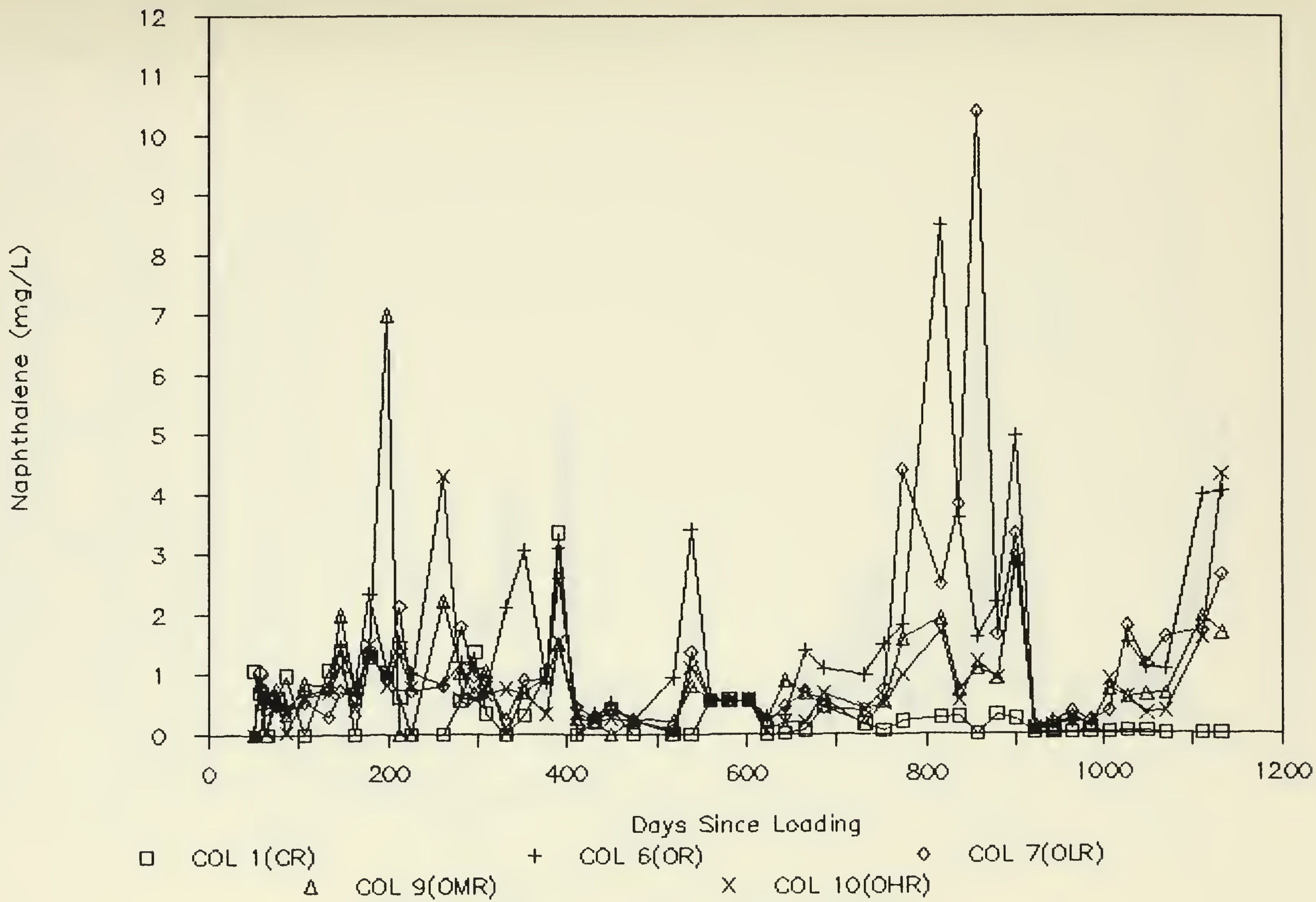


Figure 72 Leachate Naphthalene Concentrations, Single Pass Columns

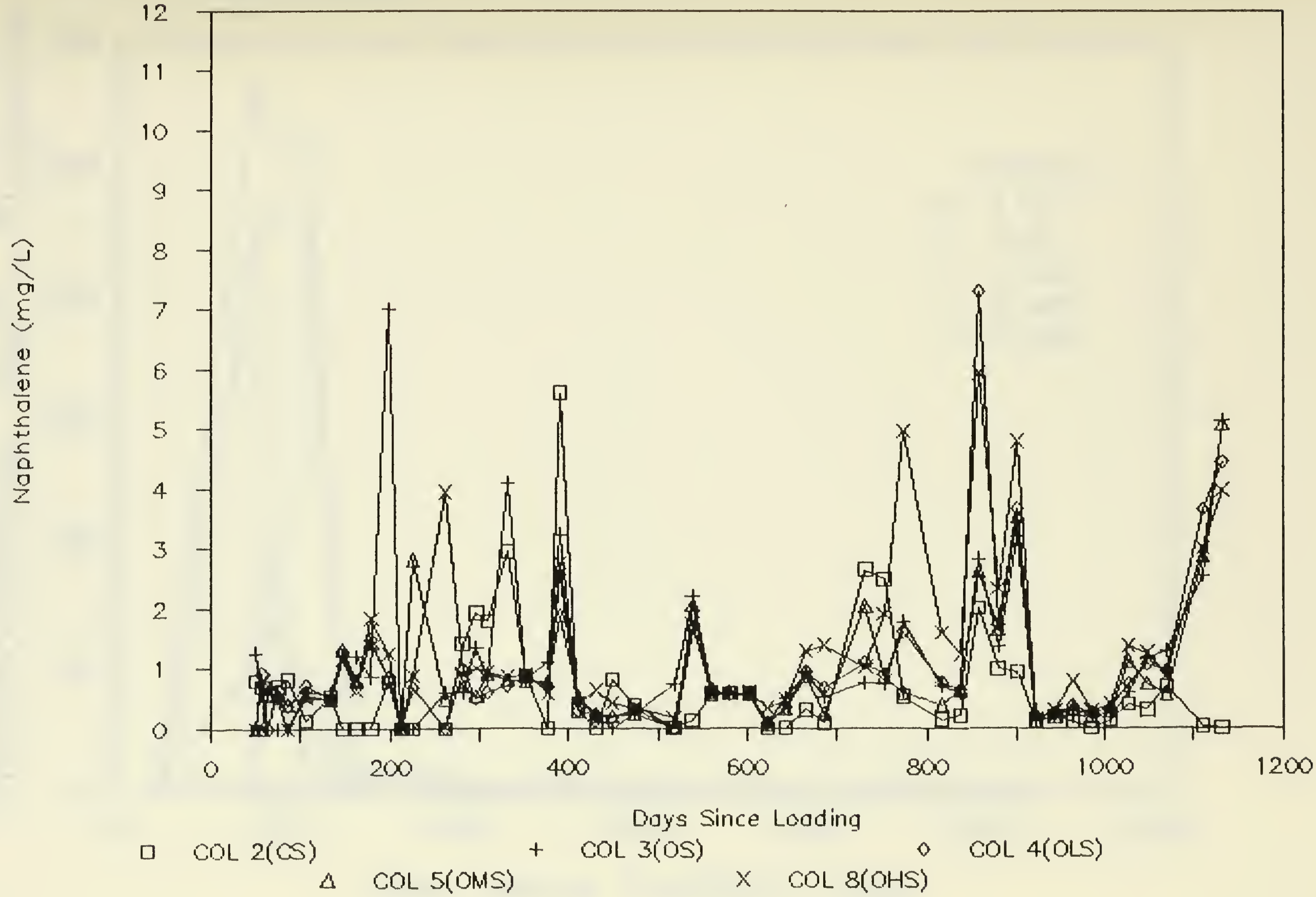


Figure 73 Leachate Dibromomethane Concentrations, Recycle Columns

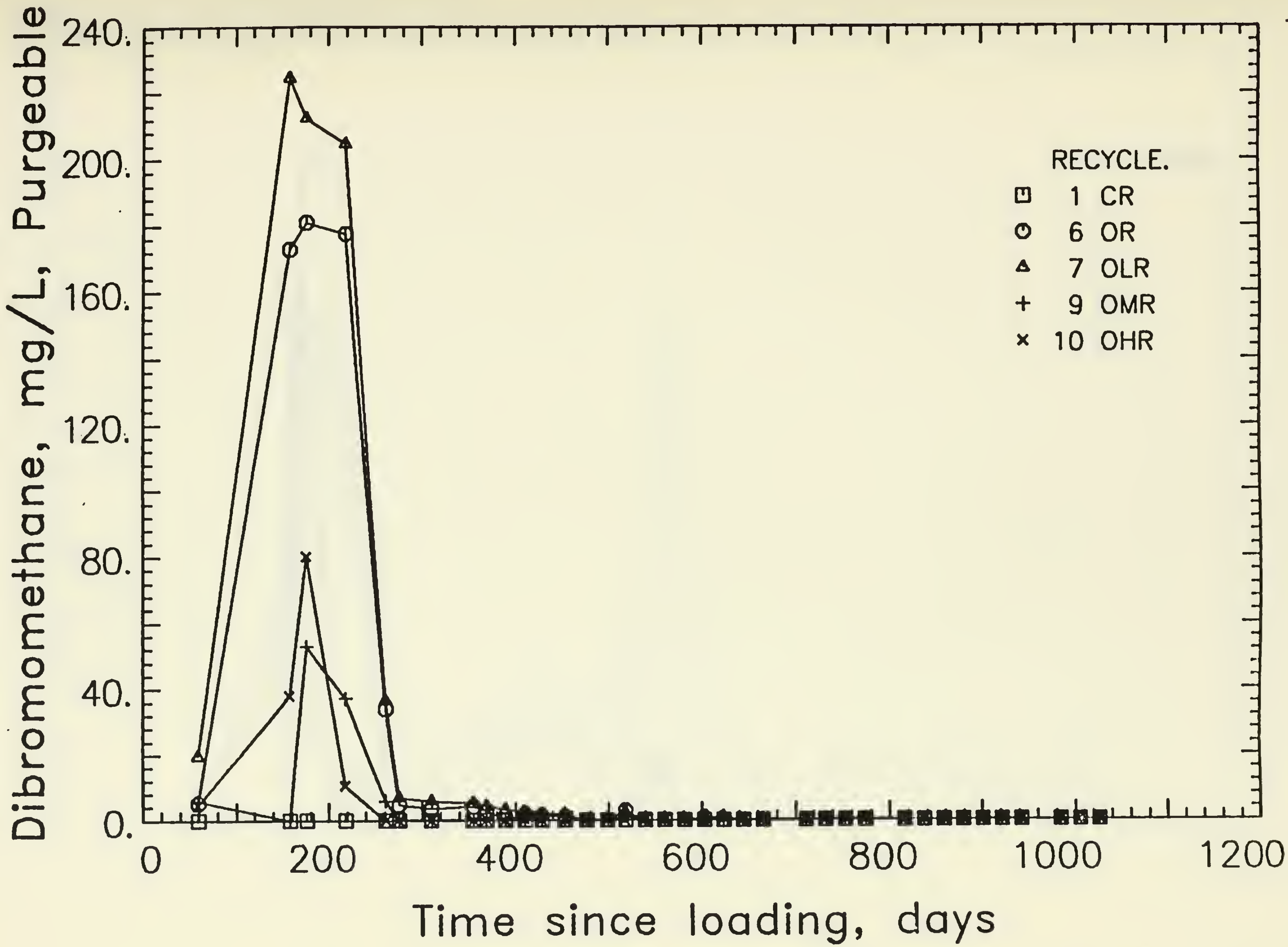


Figure 74 Leachate Dibromomethane Concentrations
Single Pass Columns

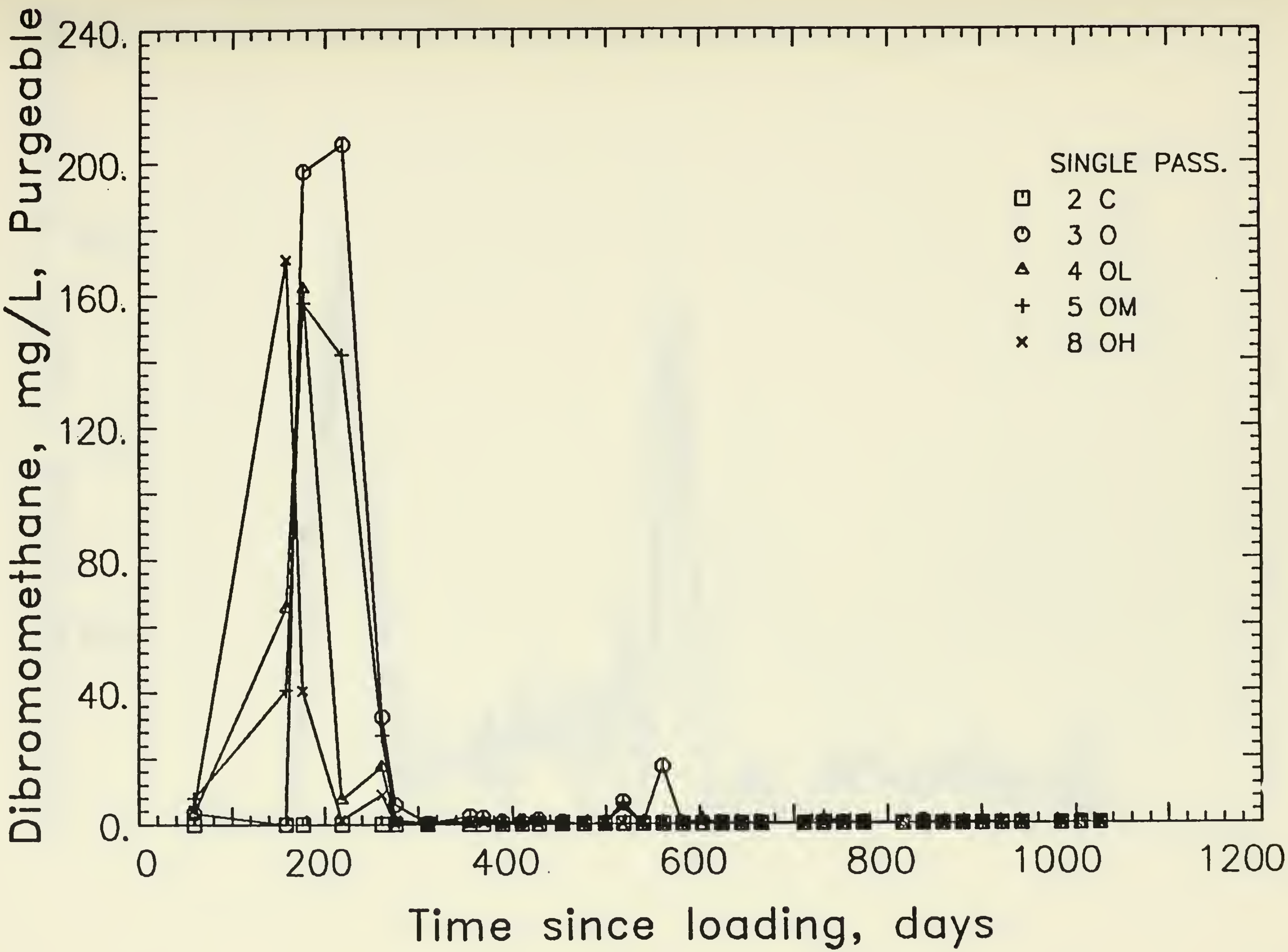


Figure 75 Leachate 1,1,2-trichloroethylene Concentrations, Recycle Columns

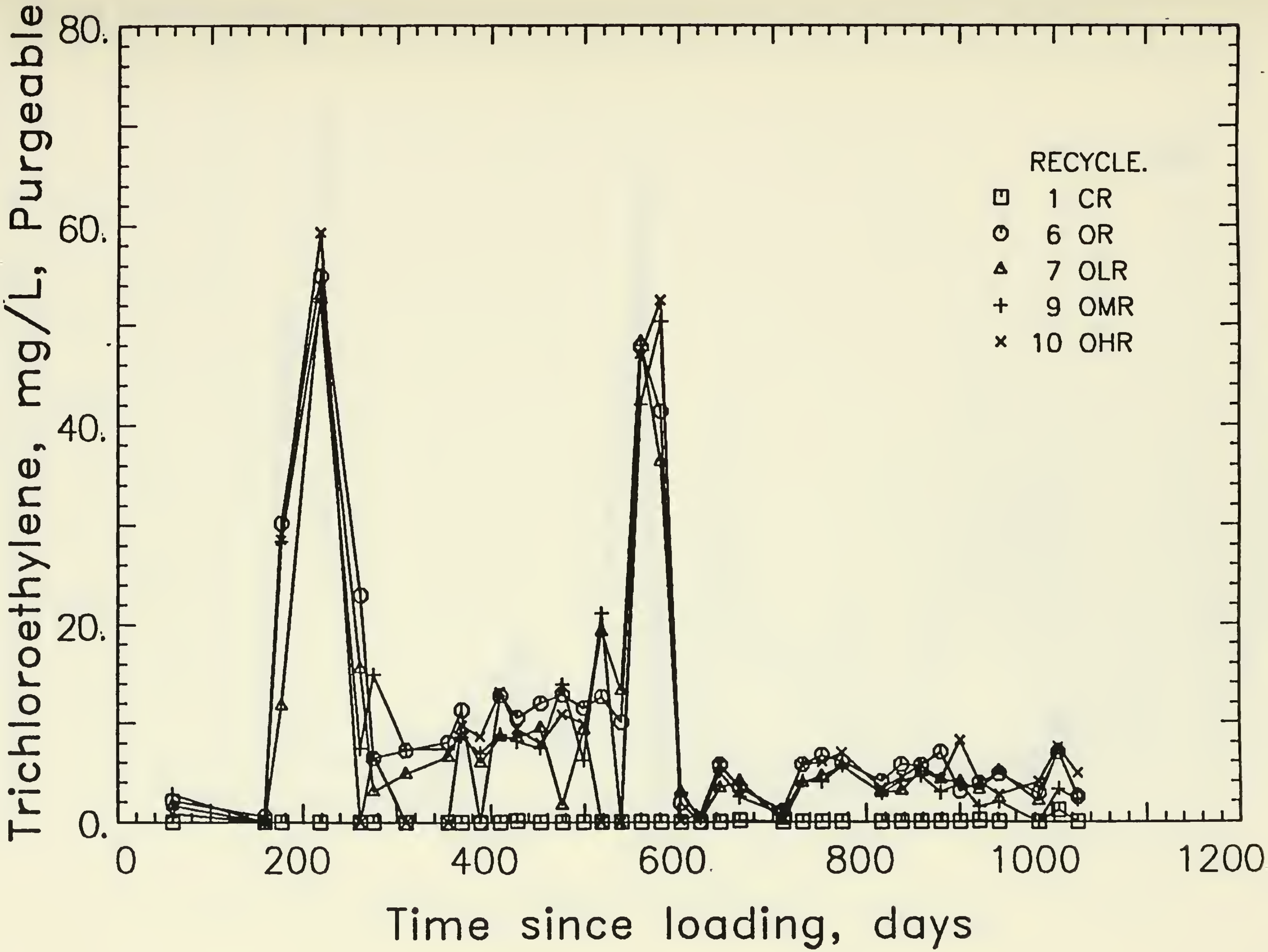


Figure 76 Leachate 1,1,2-trichloroethylene Concentrations, Single Pass Columns

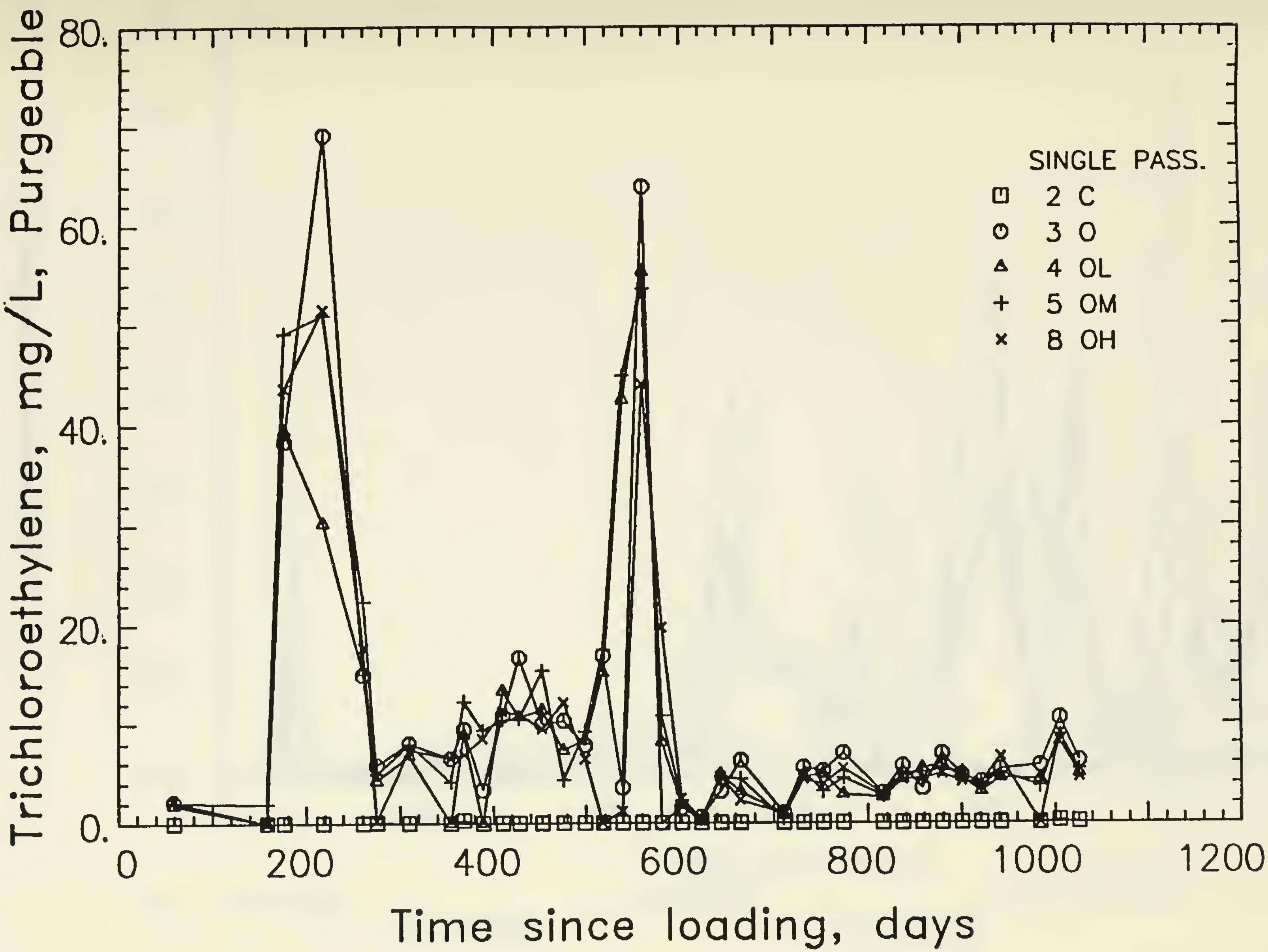


Figure 77 Leachate 1,4-dichlorobenzene Concentrations, Recycle Columns

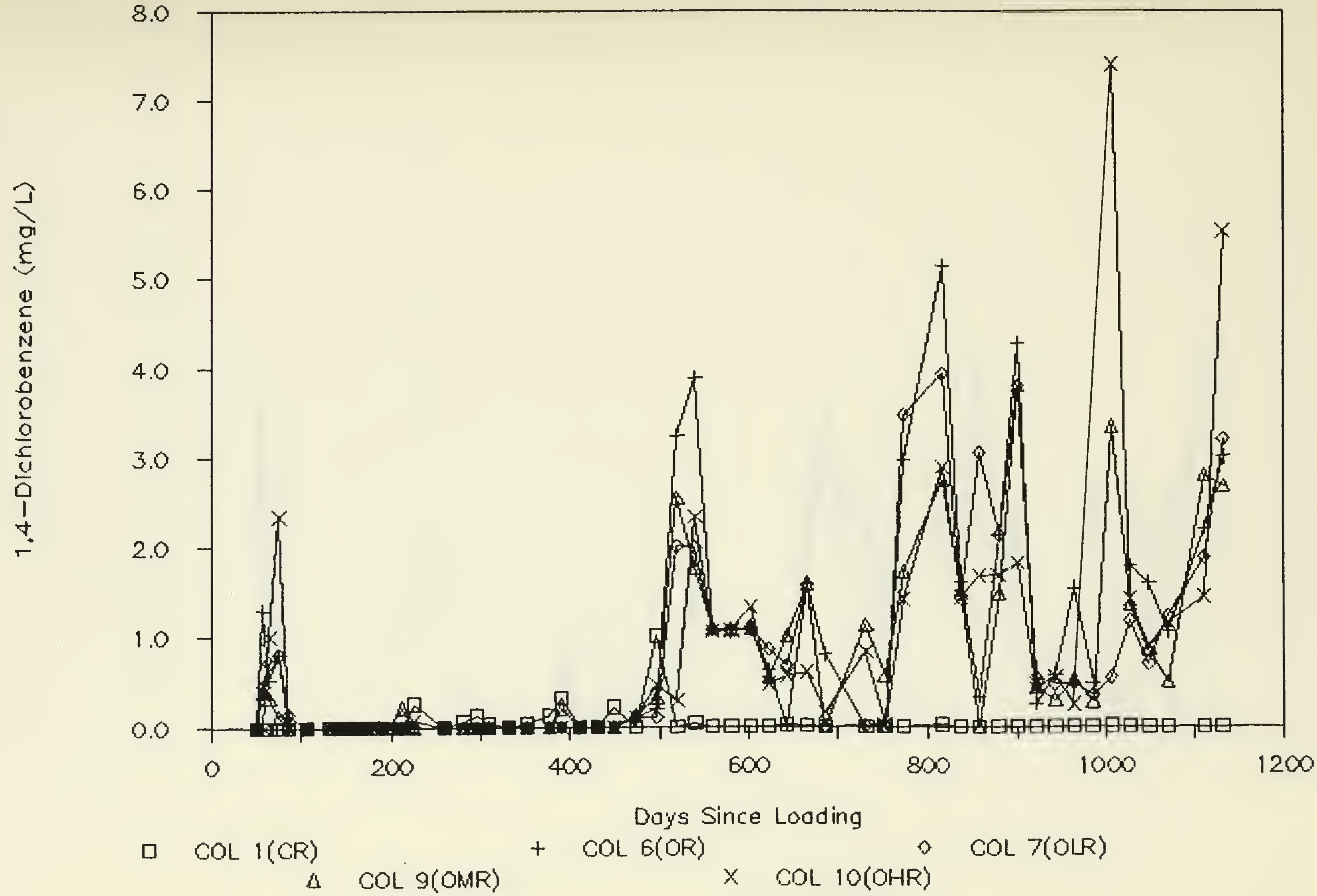


Figure 78 Leachate 1,4-dichlorobenzene Concentrations, Single Pass Columns

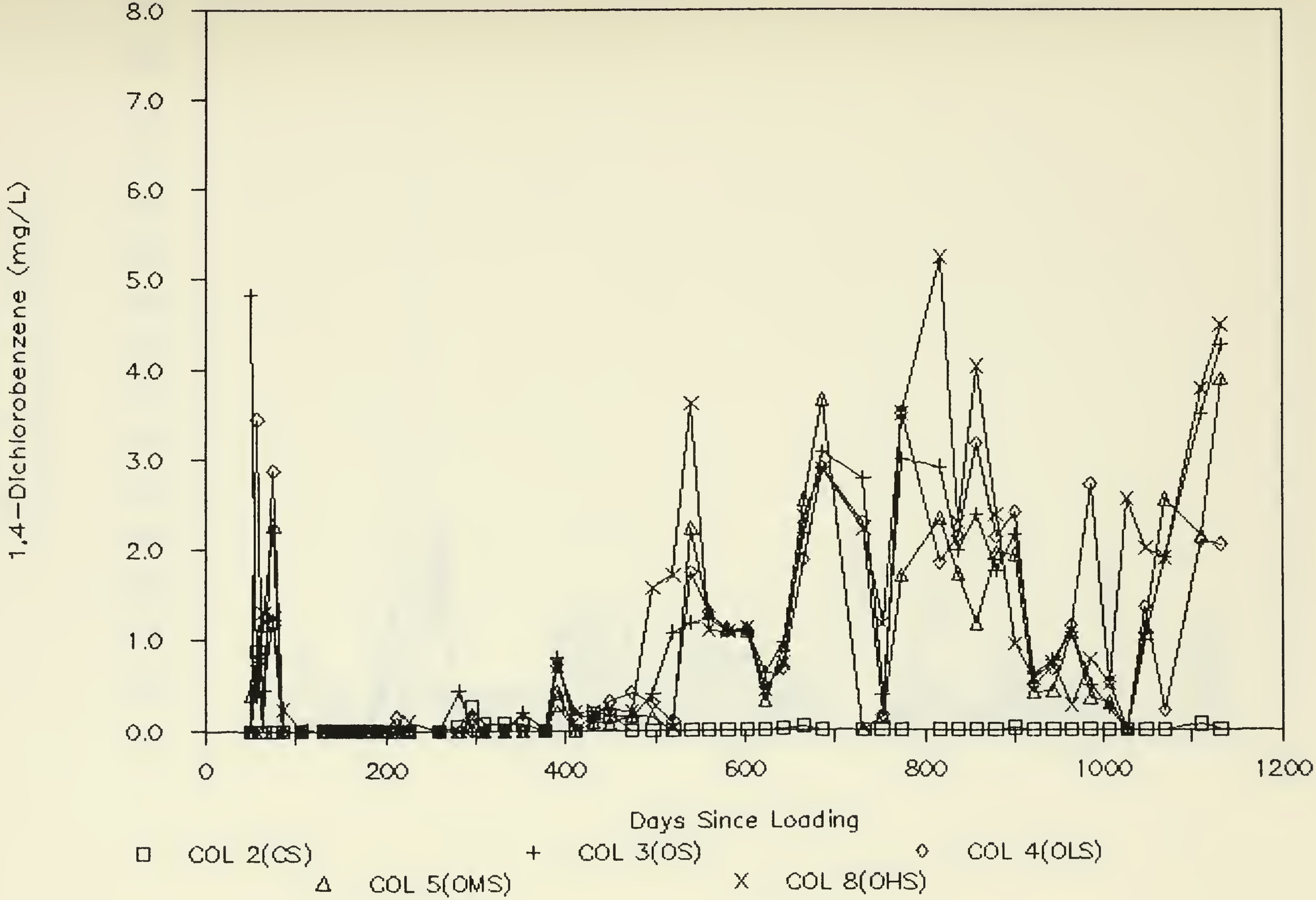


Figure 79 Leachate 1,2,4-trichlorobenzene Concentrations, Recycle Columns

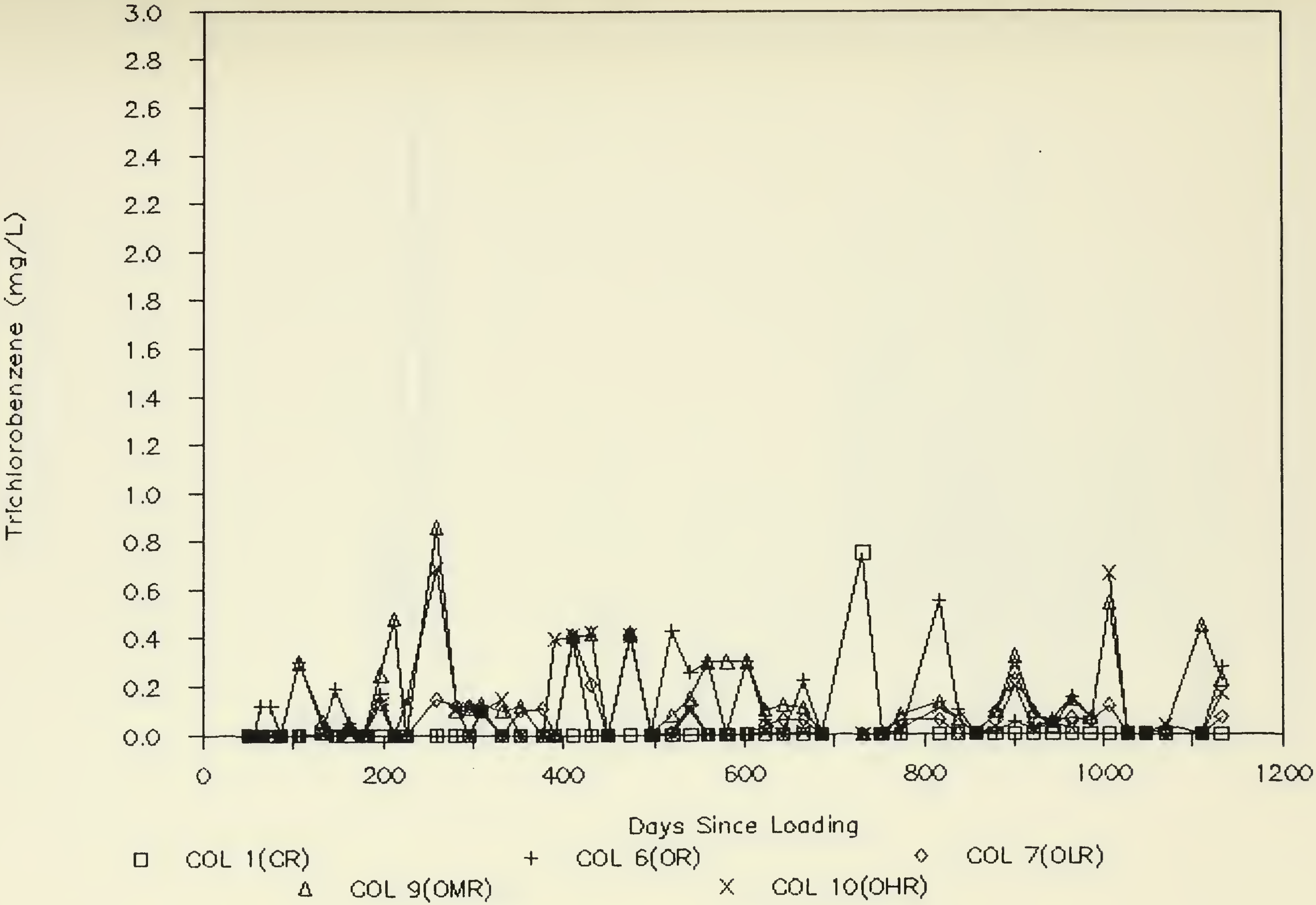


Figure 80 Leachate 1,2,4-trichlorobenzene Concentrations, Single Pass Columns

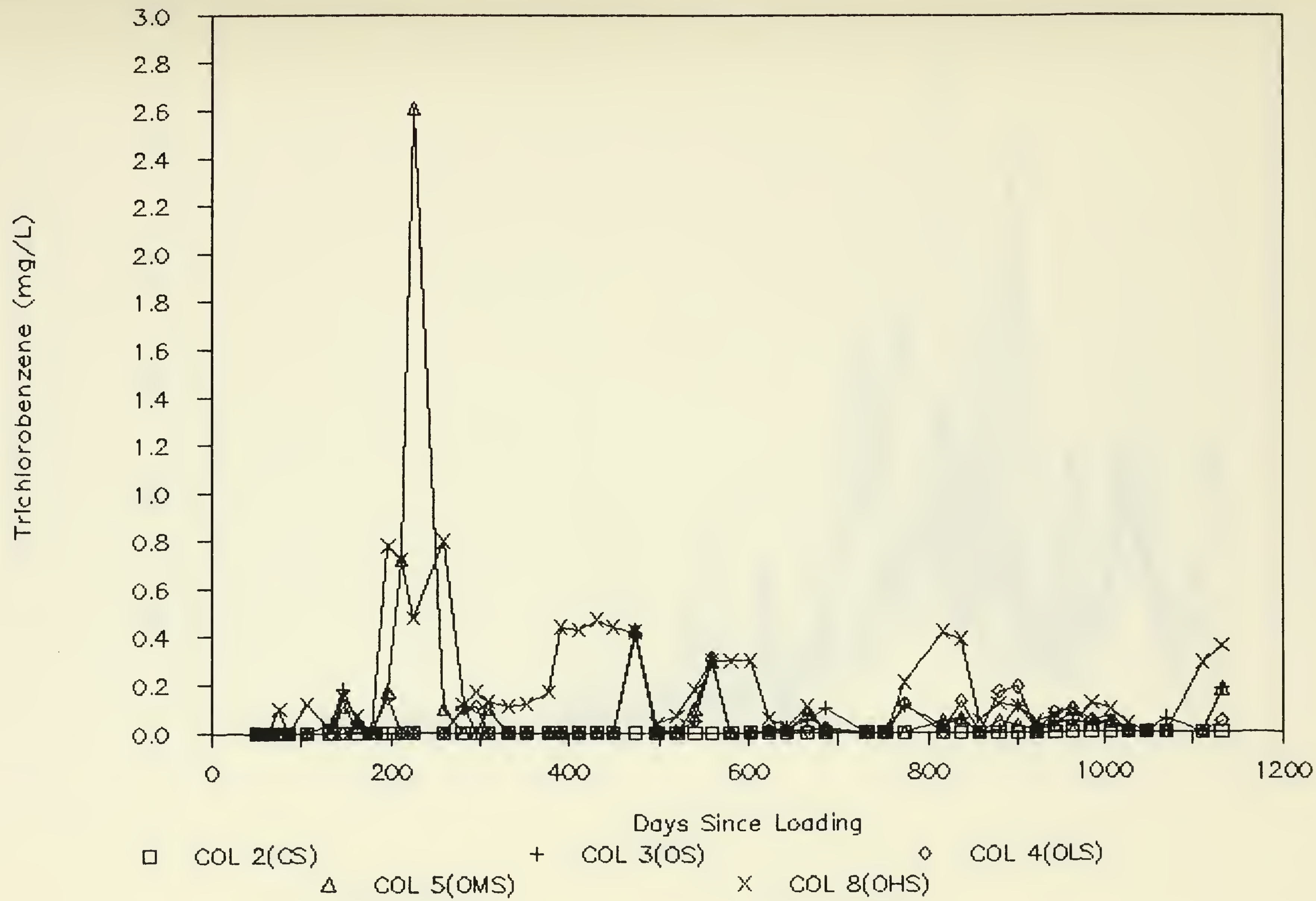


Figure 81 Leachate 2,4-dichlorophenol Concentrations, Recycle Columns

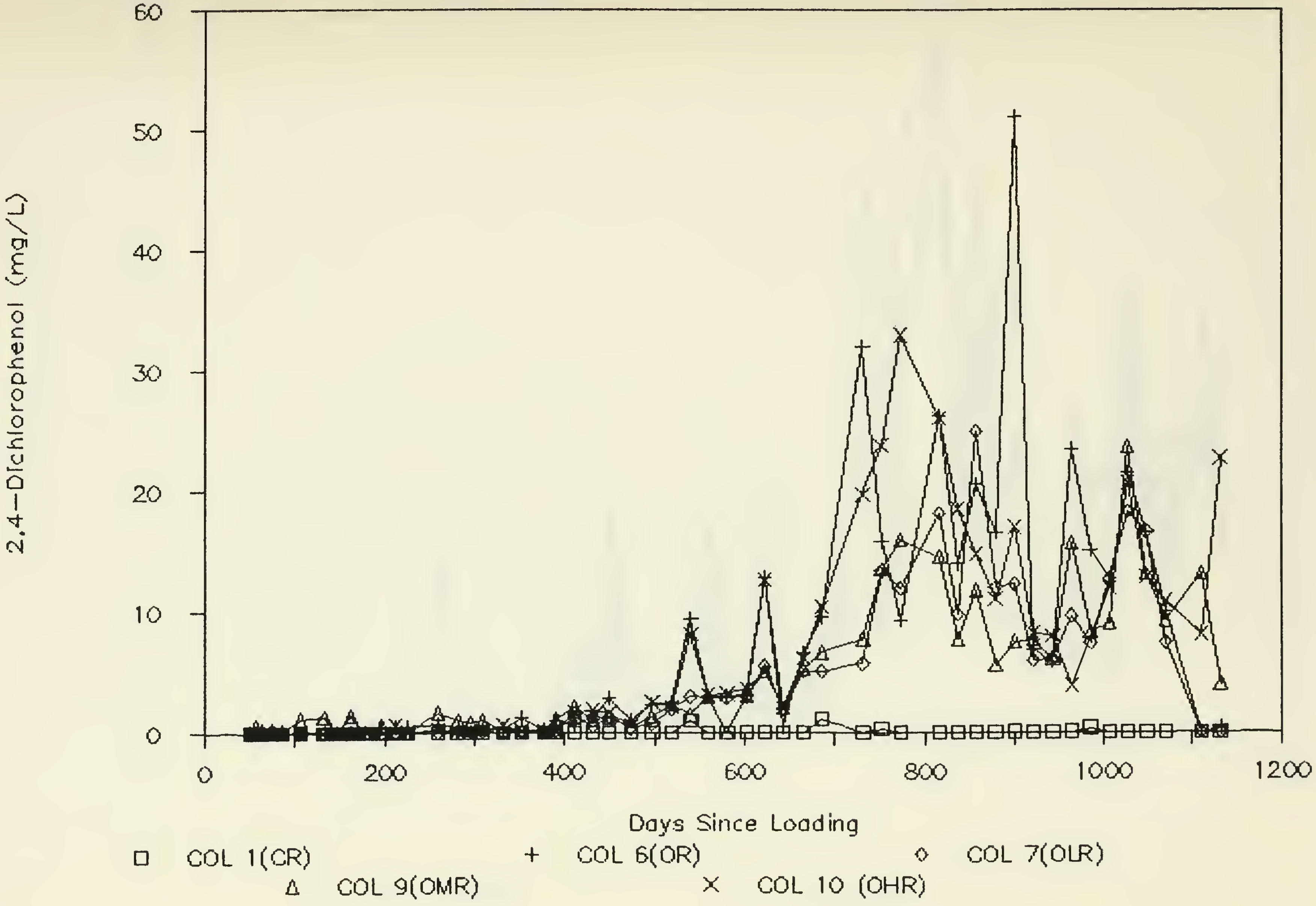
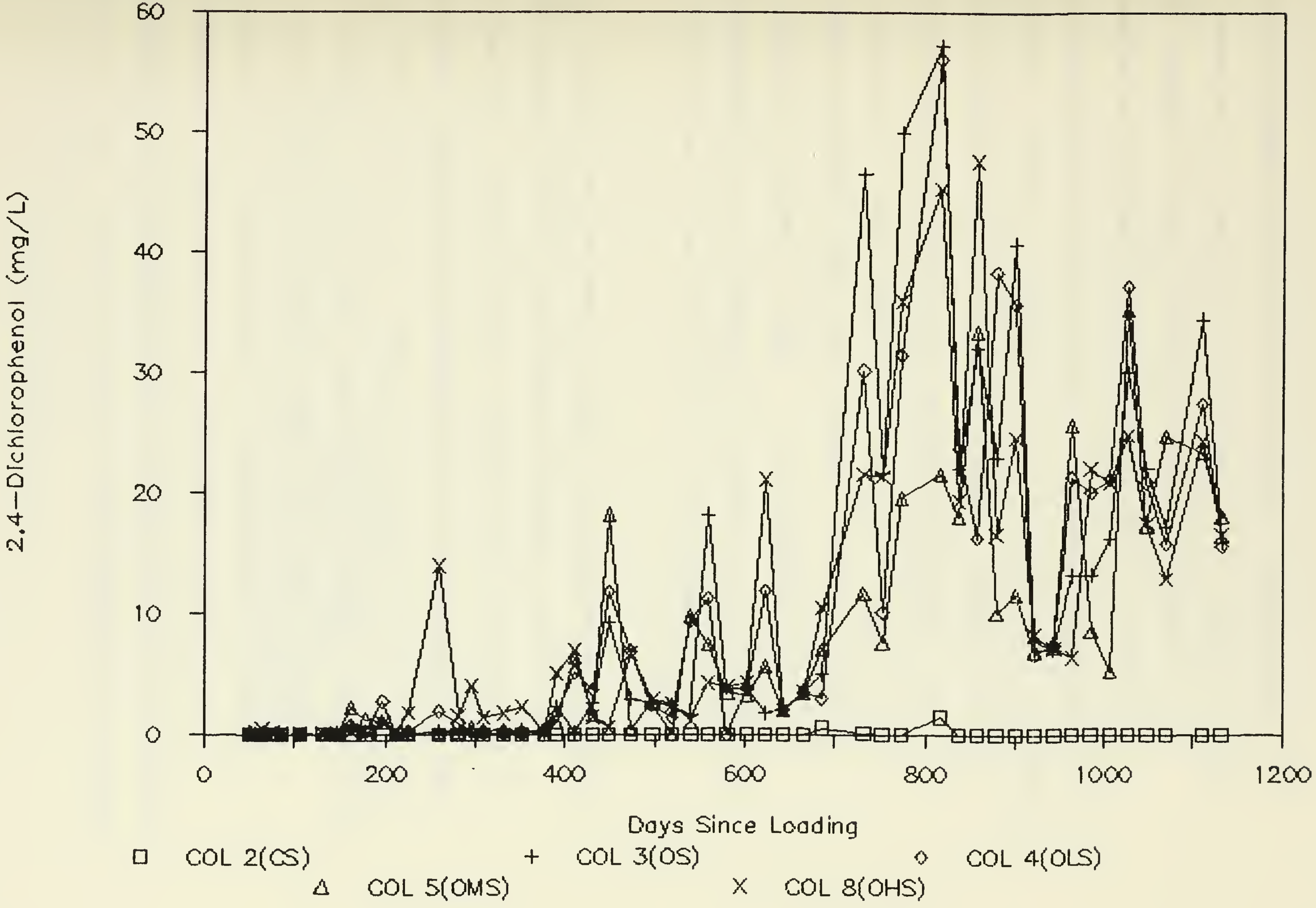


Figure 82 Leachate 2,4-dichlorophenol Concentrations, Single Pass Columns



dichlorophenol from the test columns. Nitrobenzene concentrations measured in the leachates (Figures 83 and 84) suggest an early release of this compound to the leachates followed by a precipitous drop in leachate concentrations to below detection limits between Days 700 and 800. Finally, comparison of nitrophenol levels between the leachates from the recycle columns (Figure 85) and those from the single pass columns (Figure 86) show comparatively high concentrations in the most heavily loaded (metals) single pass column, Column 8 (OHS) as compared to Column 10 (OHR). This suggests that biodegradation, as enhanced by leachate recycle, may be contributing to the attenuation of nitrophenol.

The possible mechanisms by which the _in situ_ mitigation of the organic priority pollutants occurred, include dispersion, volatilization, sorption and biodegradation. Evidence suggesting biodegradation of dibromomethane and trichloroethylene was observed in Column 3 (OS). Bromide, not present in the single pass control column, was detected in the leachate of Column 3 (OS) soon after a marked reduction in concentration of dibromomethane occurred. Similarly, vinyl chloride, a probable transformation product of trichloroethylene, was detected in the headspace gas of Column 3 (OS) following a noted decrease in leachate trichloroethylene concentration.

Figure 65 Leachate Nitrobenzene Concentrations, Recycle Columns

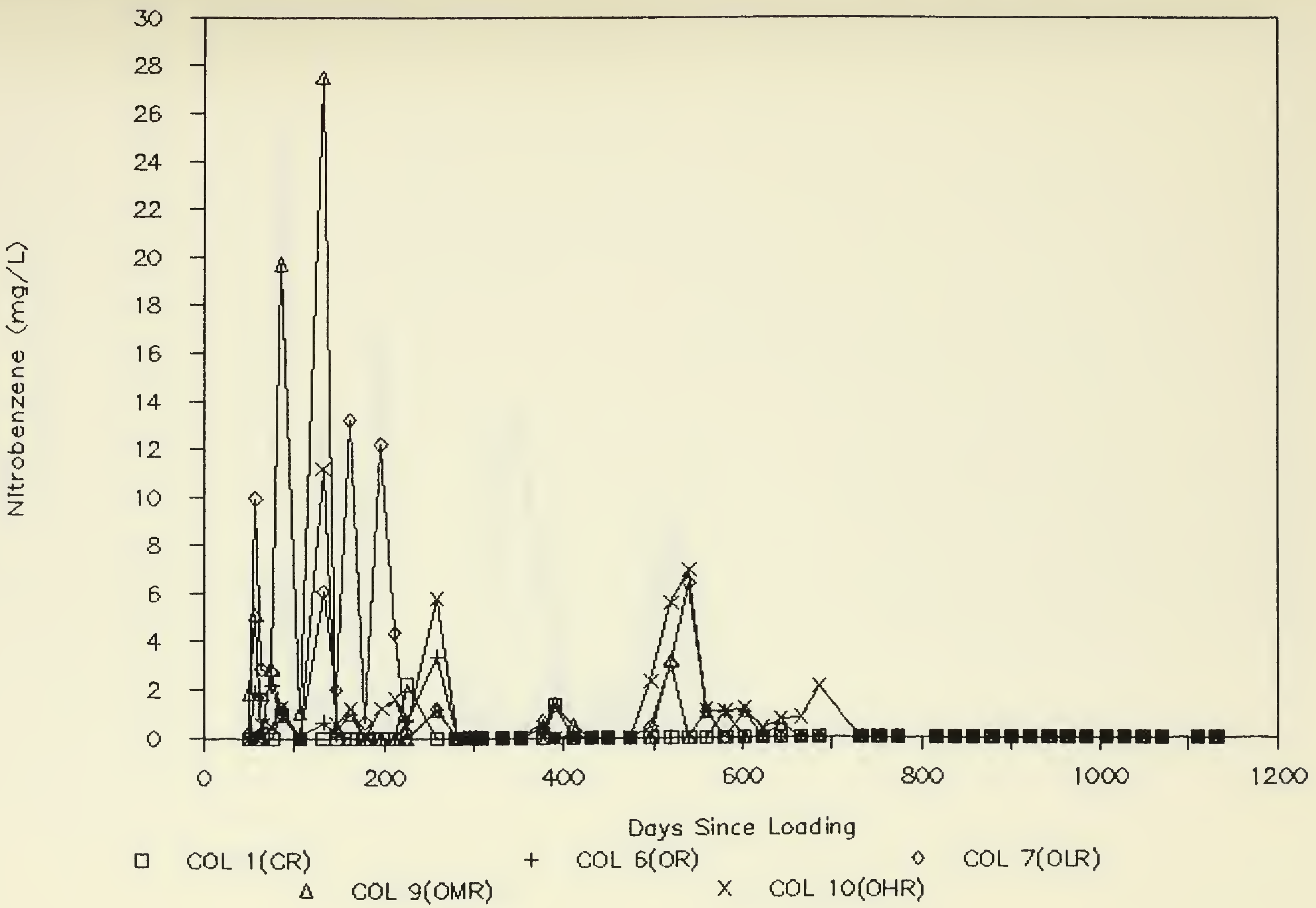


Figure 84 Leachate Nitrobenzene Concentrations, Single Pass Columns

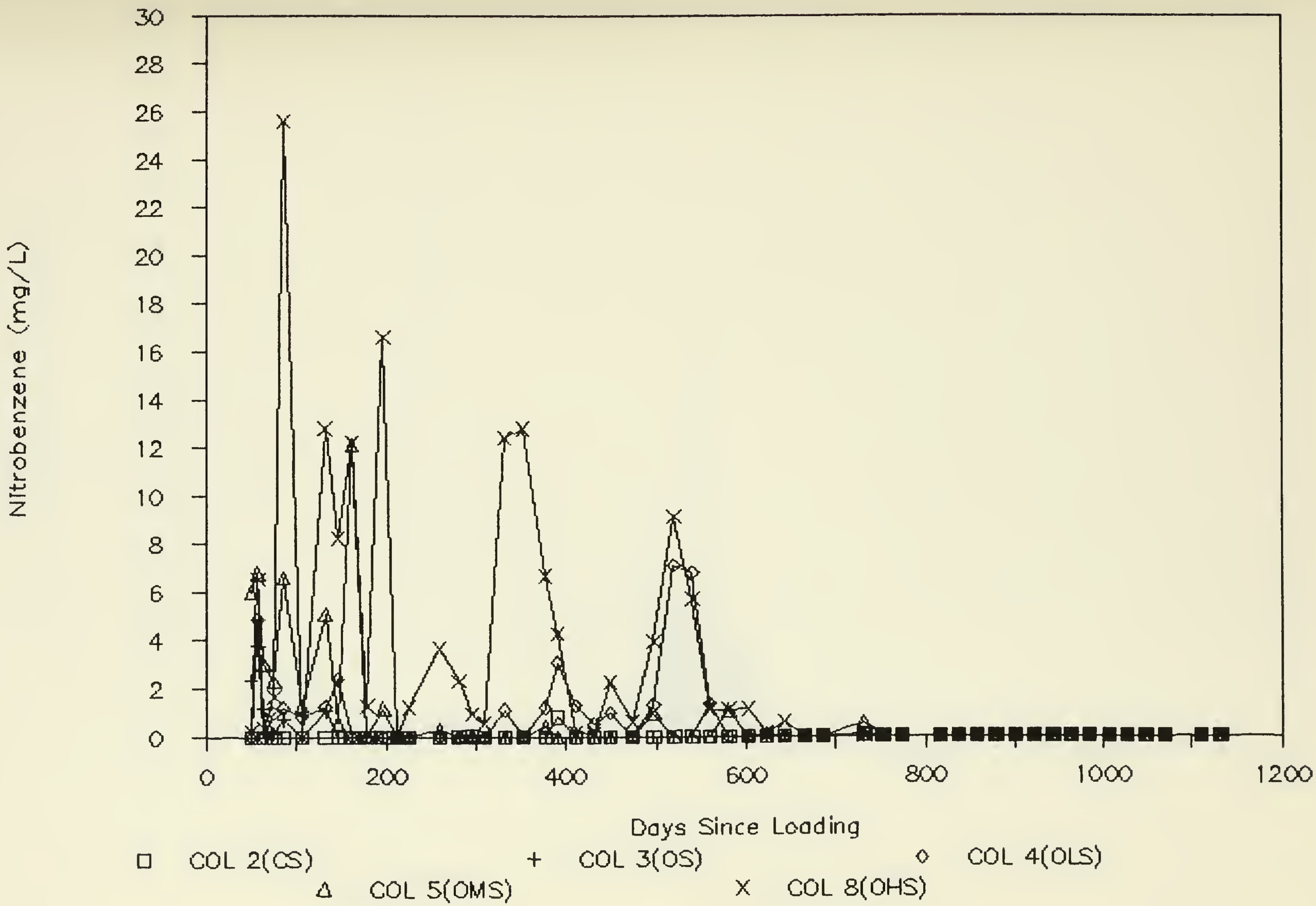


Figure 85 Leachate 2-nitrophenol Concentrations, Recycle Columns

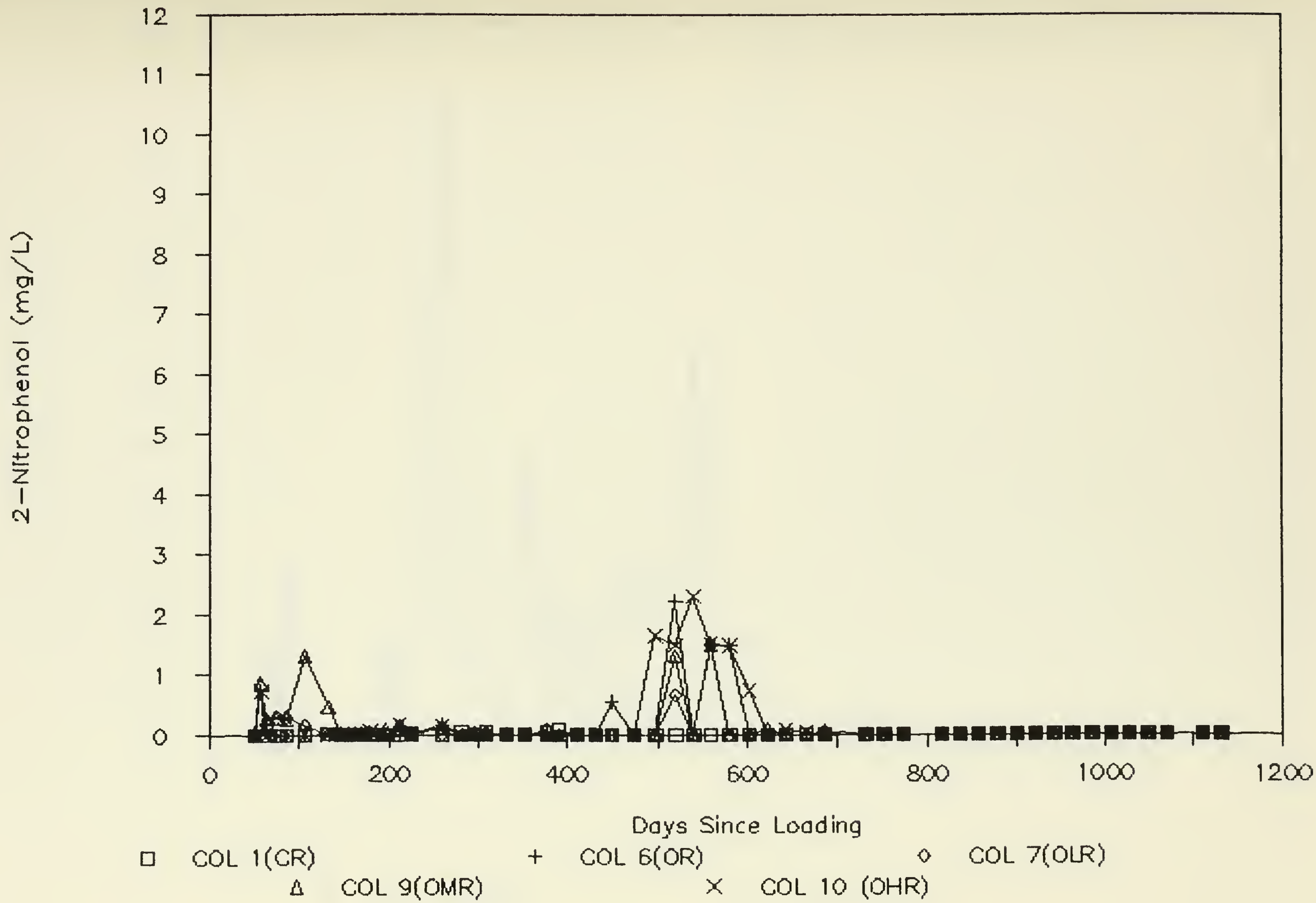
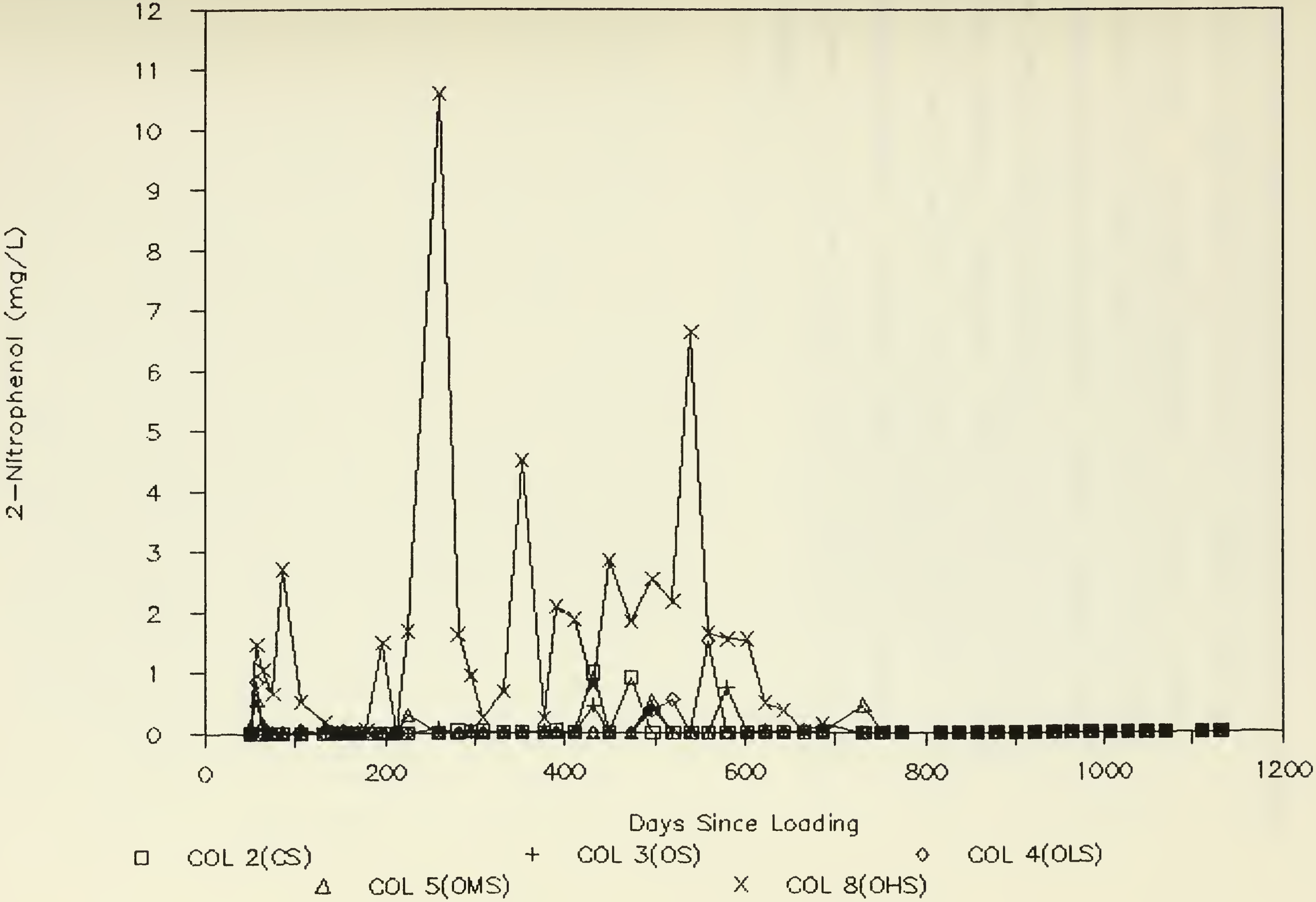


Figure 86 Leachate 2-nitrophenol Concentrations, Single Pass Columns



Concurrent bench-scale studies performed by others included sorption experiments for the twelve organic priority pollutants. In those experiments, sorption of these compounds by ground municipal refuse occurred quickly (within two hours of contact), and the organic content of the refuse largely determined the sorptive affinity for a given compound. Therefore, refuse, due to its inherent high organic content, will serve as an effective sorption medium, however, as natural stabilization processes progress, its effectiveness would be expected to decline somewhat.

Chapter V: Summary and Conclusions

The purpose of this study was to evaluate the behavior and fate of selected inorganic and organic priority pollutants codisposed with municipal solid waste in simulated landfills operated with either single pass leaching or leachate recirculation, and, through observation of relative effects on the progress of natural stabilization processes, develop a leachate management and pollutant loading strategy for codisposal landfill operations employing leachate recycle.

General Findings - Comparison of gas production and quality measurements, particularly between the respective single pass and leachate recycle control columns, provided additional evidence of the efficacy of leachate recycle as a landfill management option. Additionally, under circumstances of codisposal, the enhanced contact between leachate and the refuse mass, afforded by leachate recycle, provided greater opportunity for attenuation of the leachate priority pollutant concentrations through various biological and physical/chemical interactions. As a result, all the recycle test columns, although in varying degrees, were able to adjust to the pollutant loadings as indicated in their delayed, yet continued microbially-mediated stabilization of the refuse.

Sulfide precipitation, hydroxide precipitation, reduction and filtration were mechanisms contributing to the removal of toxic heavy metals loaded with the refuse. The high affinity for sorption of the organic priority pollutants within the refuse, particularly the non-polar and, therefore, more hydrophobic compounds, both substantially prevented migration of these contaminants and provided the retention necessary to allow biodegradation of susceptible compounds.

The organic loadings applied (in terms of COD) as a result of leachate recycle generally remained within the optimum range observed in previous investigations of the anaerobic treatment of landfill leachates. Limited by leachate production, however, the effects of higher organic loadings could not be examined.

<u>Proposed Leachate Management and Pollutant Loading Strategy</u>

<u>Leachate Management</u> - The impact of leachate recycle rates was most evident during the seeding process used to firmly establish the methane production phase of landfill stabilization. As was discussed, significant improvements in methane production during this process were not observed until the seeding protocol was modified to include neutralization of the small quantities of leachate which

were added to the anaerobic digester sludge seed as a source of readily available substrate. This demonstrated the sensitivity of the simulated landfills to acid shock loadings resulting form leachate recycle, even with the infrequent, and small amounts recycled during the first (unneutralized) phase of seeding (Seedings 1-8, Appendix I).

However, as methane production became well established, concomitant decreases in volatile acid concentrations allowed the increase of recycle rates to 12 liters per day, without observable detriment to gas production.

The indication from these results is that an overall leachate recycle strategy must consider the potential for acid shock loadings during the crucial transition from the acid phase of stabilization to the methanogenic phase. While small, neutralized recycle quantities appears necessary for the establishment of methanogenesis, increased recycle rates may be used as the conversion of volatile acids increases, with the associated rise in pH.

Increasing recycle rates during active methane fermentation will also enhance the stabilization process as intimate contact between the substrate and the microbial flora is increased. However, as experienced in the present study, leachate production limitations may occur, necessitating

decreases in recycle rates and frequency. This may prevent the taking of full advantage of this accelerating effect.

The leachate limitation experienced supports the notion of maintaining a moist landfill during the years of active stabilization. Then, after the landfill matures, capping and drying of the landfill through final leachate collection, treatment, and ultimate disposal (possibly to a POTW) would be appropriate.

Pollutant Loading - Relative cumulative gas production among the recycle columns served as the primary indicator of the degree of toxicity experienced in each column. Based on this data, and the known manner in which the priority pollutants were added, general conclusions regarding the mass loadings of the applied pollutants, as well as the application method, can be drawn.

The comparison of cumulative gas production among the loaded recycle columns, (Figures 32 and 33), revealed some inhibition of stabilization in the column loaded with only organic priority pollutants. In that case, Column 6 (OR) had a total gas production 84 percent of the control. More profound toxic effects were noted in those columns which, in addition to the organics, also received varying quantities of heavy metals. These columns, Columns 7

[illegible]

[illegible]

[illegible]

(OLR), 9 (OMR), and 10 (OHR), produced 47, 49, and 38 percent of the gas produced by Column 1 (CR). As discussed, no statistically significant difference was found between the gas production of Columns 7 (OLR) and 9 (OMR). This suggested that a loading threshold was exceeded in the metals loading to Column 10 (OHR).

Proposing a loading limit for the metals applied in this experiment requires acceptance of some degree of inhibition. If, for instance, 50 percent inhibition is an acceptable, then the recommended loadings for the metals applied herein would be those applied to Column 9 (OMR) (Table 14). In order to develop a more concise tool for predicting the degree of toxicity caused by specific loadings, experimental data over a wider range of loadings would be beneficial.

Perhaps more important than the gross metal loadings is the manner in which the metal sludge/sawdust mixtures were applied. As suggested by this study, application of such sludges in discrete layers, as opposed to thoroughly mixing with municipal solid waste, should provide a greater assurance of containment and assimilation of the metals leached from the applied chemical sludge. Discrete layers of this source of toxicity will also allow the development of the microbial community necessary for the degradation of the waste, and, to some degree, attenuation of the

pollutants. However, since varying degrees of mixing were not a variable specifically examined in the present study, future research efforts would provide a factual evaluation of this inference.

APPENDIX I

Leachate Recycle Volumes (Liters)

Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	Notes
139	-	-	-	-	-	- Recycled approximately
to						every three days, but volume
662	-	-	-	-	-	recycled was not measured
663	0.0	0.0	0.0	0.0	0.0	
664	0.0	0.0	0.0	0.0	0.0	
665	0.0	0.0	0.0	0.0	0.0	
666	0.0	0.0	0.0	0.0	0.0	- No routine recycle, as
667	0.0	0.0	0.0	0.0	0.0	"seeding" with anaerobic
668	0.0	0.0	0.0	0.0	0.0	digester sludge was initiated
669	0.0	0.0	0.0	0.0	0.0	on day 666
670	0.0	0.0	0.0	0.0	0.0	
671	0.0	0.0	0.0	0.0	0.0	
672	0.0	0.0	0.0	0.0	0.0	
673	0.0	0.0	0.0	0.0	0.0	
674	0.0	0.0	0.0	0.0	0.0	
675	0.0	0.0	0.0	0.0	0.0	
676	0.0	0.0	0.0	0.0	0.0	
677	0.0	0.0	0.0	0.0	0.0	
678	0.0	0.0	0.0	0.0	0.0	
679	0.0	0.0	0.0	0.0	0.0	
680	0.0	0.0	0.0	0.0	0.0	
681	0.0	0.0	0.0	0.0	0.0	
682	0.0	0.0	0.0	0.0	0.0	
683	0.0	0.0	0.0	0.0	0.0	
684	2.0	2.0	2.0	2.0	2.0	- Prior to 2nd seeding
685	0.0	0.0	0.0	0.0	0.0	
686	0.0	0.0	0.0	0.0	0.0	
687	0.0	0.0	0.0	0.0	0.0	
688	0.0	0.0	0.0	0.0	0.0	
689	0.0	0.0	0.0	0.0	0.0	
690	0.0	0.0	0.0	0.0	0.0	
691	0.0	0.0	0.0	0.0	0.0	
692	0.0	0.0	0.0	0.0	0.0	
693	0.0	0.0	0.0	0.0	0.0	
694	0.0	0.0	0.0	0.0	0.0	
695	0.0	0.0	0.0	0.0	0.0	
696	0.0	0.0	0.0	0.0	0.0	
697	0.0	0.0	0.0	0.0	0.0	
698	0.0	0.0	0.0	0.0	0.0	
699	0.0	0.0	0.0	0.0	0.0	
700	0.0	0.0	0.0	0.0	0.0	
701	0.0	0.0	0.0	0.0	0.0	
702	0.0	0.0	0.0	0.0	0.0	- 3rd seeding
703	0.0	0.0	0.0	0.0	0.0	
704	0.0	0.0	0.0	0.0	0.0	
705	0.0	0.0	0.0	0.0	0.0	
706	0.0	0.0	0.0	0.0	0.0	

Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	Notes
707	0.0	0.0	0.0	0.0	0.0	
708	0.0	0.0	0.0	0.0	0.0	
709	0.0	0.0	0.0	0.0	0.0	
710	0.0	0.0	0.0	0.0	0.0	
711	0.0	0.0	0.0	0.0	0.0	
712	0.0	0.0	0.0	0.0	0.0	
713	0.0	0.0	0.0	0.0	0.0	
714	0.0	0.0	0.0	0.0	0.0	
715	0.0	0.0	0.0	0.0	0.0	
716	0.0	0.0	0.0	0.0	0.0	
717	0.0	0.0	0.0	0.0	0.0	
718	0.0	0.0	0.0	0.0	0.0	
719	0.0	0.0	0.0	0.0	0.0	
720	0.0	0.0	0.0	0.0	0.0	
721	0.0	0.0	0.0	0.0	0.0	
722	2.0	2.0	2.0	2.0	2.0	- Recycle pump operational test
723	0.0	0.0	0.0	0.0	0.0	- 4th seeding
724	0.0	0.0	0.0	0.0	0.0	
725	0.0	0.0	0.0	0.0	0.0	
726	0.0	0.0	0.0	0.0	0.0	
727	0.0	0.0	0.0	0.0	0.0	
728	0.0	0.0	0.0	0.0	0.0	
729	0.0	0.0	0.0	0.0	0.0	
730	0.0	0.0	0.0	0.0	0.0	
731	0.0	0.0	0.0	0.0	0.0	
732	0.0	0.0	0.0	0.0	0.0	
733	0.0	0.0	0.0	0.0	0.0	
734	0.0	0.0	0.0	0.0	0.0	
735	0.0	0.0	0.0	0.0	0.0	
736	0.0	0.0	0.0	0.0	0.0	
737	0.0	0.0	0.0	0.0	0.0	
738	0.0	0.0	0.0	0.0	0.0	
739	0.0	0.0	0.0	0.0	0.0	
740	2.0	2.0	2.0	2.0	2.0	- Prior to 5th seeding
741	0.0	0.0	0.0	0.0	0.0	
742	0.0	0.0	0.0	0.0	0.0	
743	2.2	2.8	1.3	1.5	1.5	
744	0.0	0.0	0.0	0.0	0.0	
745	0.0	0.0	0.0	0.0	0.0	
746	0.0	0.0	0.0	0.0	0.0	
747	2.3	6.2	1.5	0.0	2.0	
748	0.0	0.0	0.0	0.0	0.0	
749	3.0	4.0	3.5	4.0	4.5	- Prior to 6th seeding
750	0.0	0.0	0.0	0.0	0.0	
751	0.0	0.0	0.0	0.0	0.0	
752	0.0	0.0	0.0	0.0	0.0	
753	0.0	0.0	0.0	0.0	0.0	
754	3.0	4.0	3.0	3.0	4.5	
755	0.0	0.0	0.0	0.0	0.0	
756	0.0	0.0	0.0	0.0	0.0	
757	3.0	4.0	3.0	3.0	4.5	

Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	Notes
758	0.0	0.0	0.0	0.0	0.0	
759	0.0	0.0	0.0	0.0	0.0	
760	0.0	0.0	0.0	0.0	0.0	
761	3.0	4.0	3.0	3.0	4.5	- Prior to 7th seeding
762	1.5	4.0	2.5	3.0	4.0	
763	1.5	4.0	2.5	3.0	4.0	
764	1.5	4.0	2.5	3.0	4.0	
765	1.5	4.0	2.5	3.0	4.0	
766	1.5	4.0	2.5	3.0	4.0	
767	1.5	4.0	2.5	3.0	4.0	
768	1.5	4.0	2.5	3.0	4.0	
769	1.5	4.0	2.5	3.0	4.0	
770	1.5	4.0	2.5	3.0	4.0	- Prior to 8th seeding
771	1.5	4.0	2.5	3.0	4.0	
772	1.5	4.0	2.5	3.0	4.0	
773	0.0	0.0	0.0	0.0	0.0	
774	0.0	0.0	0.0	0.0	0.0	
775	1.0	1.0	1.0	1.0	1.0	- pH adjusted to 5-6 range
776	0.0	0.0	0.0	0.0	0.0	through the addition of
777	1.5	4.0	2.5	3.0	4.0	Na2CO3 (150 g/L solution),
778	0.0	0.0	0.0	0.0	0.0	recycled as part of the
779	0.0	0.0	0.0	0.0	0.0	9th seeding mixture
780	0.0	0.0	0.0	0.0	0.0	
781	0.0	0.0	0.0	0.0	0.0	
782	2.0	2.0	2.0	2.0	2.0	- 1.0 L pH-adjusted leachate (6-7),
783	2.0	2.0	2.0	2.0	2.0	" using 150 g/L Na2CO3, recycled
784	2.0	2.0	2.0	2.0	2.0	" twice per day
785	2.0	2.0	2.0	2.0	2.0	" " " "
786	2.0	2.0	2.0	2.0	2.0	" " " "
787	2.0	2.0	2.0	2.0	2.0	" " " "
788	2.0	2.0	2.0	2.0	2.0	" " " "
789	2.0	2.0	2.0	2.0	2.0	" " " "
790	1.8	1.8	1.8	1.8	1.8	- pH adjusted to 6-7
791	1.8	1.8	1.8	1.8	1.8	" "
792	1.0	1.0	1.0	1.0	1.0	- pH adjusted to 5-6 range through
793	1.8	1.8	1.8	1.8	1.8	addition of Na2CO3 (150 g/L solution),
794	1.8	1.8	1.8	1.8	1.8	recycled as part of 10th seeding mixture,
795	1.8	1.8	1.8	1.8	1.8	- pH adjusted to 6-7
796	1.8	1.8	1.8	1.8	1.8	" "
797	1.8	1.8	1.8	1.8	1.8	" "
798	1.8	1.8	1.8	1.8	1.8	" "
799	1.8	1.8	1.8	1.8	1.8	" "
800	1.8	1.8	1.8	1.8	1.8	" "
801	1.8	1.8	1.8	1.8	1.8	" "
802	1.8	1.8	1.8	1.8	1.8	" "
803	1.8	1.8	1.8	1.8	1.8	" "
804	1.0	1.0	1.0	1.0	1.0	- pH adjusted to 5-6 range through
805	1.8	1.8	1.8	1.8	1.8	addition of Na2CO3 (150 g/L solution),
806	1.8	1.8	1.8	1.8	1.8	recycled as part of 11th seeding mixture
807	3.0	3.0	3.0	3.0	3.0	
808	1.5	1.8	1.5	1.8	1.5	

Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	Notes
809	1.8	1.8	1.8	1.8	1.8	
810	3.0	3.0	3.0	3.0	3.0	
811	4.0	4.0	4.0	4.0	4.0	
812	5.0	5.0	5.0	5.0	5.0	
813	7.0	7.0	7.0	7.0	7.0	- Includes 1.0 liter which was
814	7.5	7.5	7.5	7.5	7.5	pH adjusted to 5-6 range through
815	9.0	9.0	9.0	9.0	9.0	addition of Na2CO3 (150 g/L solution)
816	10.5	10.5	10.5	10.5	10.5	and recycled as part of
817	12.0	12.0	12.0	12.0	12.0	the 12th seeding mixture
818	6.0	6.0	3.0	3.0	13.5	
819	0.5	15.0	0.0	0.0	15.0	
820	0.0	16.5	0.0	0.0	16.5	
821	0.0	16.5	0.0	0.0	18.0	
822	1.0	16.0	1.0	1.0	19.0	- Includes 1.0 liter which was
823	5.0	15.0	0.0	0.0	19.5	pH adjusted to 5-6 range through
824	0.0	13.5	0.0	0.0	18.0	addition of Na2CO3 (150 g/L solution)
825	0.0	0.0	0.0	0.0	0.0	and recycled as part of
826	0.0	9.0	0.0	0.0	19.5	the 13th seeding mixture
827	0.0	9.0	0.0	0.0	20.0	
828	0.0	13.0	0.0	0.5	19.5	
829	0.0	13.0	0.0	0.0	19.5	
830	0.0	9.0	0.0	2.0	18.8	
831	0.0	0.0	0.0	0.0	0.0	
832	3.0	3.0	3.0	3.0	3.0	
833	2.8	2.8	2.8	2.8	2.8	- Includes 1.0 liter pH adjusted to 5-6 range
834	1.8	1.8	1.8	1.8	1.8	with Na2CO3 (150 g/L solution), recycled
835	1.8	1.8	1.8	1.8	1.8	as part of 14th seeding mixture. Also,
836	1.8	1.8	1.8	1.8	1.8	addition of Na2CO3 to recycled leachate
837	1.8	1.8	1.8	1.8	1.8	was restarted as COL 7 gas production
838	1.8	1.8	1.8	1.8	1.8	was low. 16 mLs Na2CO3 were added on day
839	1.8	1.8	1.8	1.8	1.8	833 and then doses were gradually
840	1.8	1.8	1.8	1.8	1.8	decreased to only 4 mLs on day 841.
841	1.8	37.8	1.8	1.8	1.8	- COL 6 recycle included recovered leakage
842	9.0	13.0	9.0	9.0	9.0	- Includes 3.0 liters which was
843	13.0	13.0	13.0	13.0	13.0	pH adjusted to 5-6 range with
844	25.0	12.0	20.0	0.0	25.0	Na2CO3 and recycled as part of
845	25.0	12.0	20.0	10.0	25.0	15th seeding mixture
846	25.0	12.0	20.0	10.0	25.0	
847	12.0	11.0	12.0	12.0	12.0	
848	12.0	12.0	12.0	12.0	12.0	
849	13.0	13.0	13.0	13.0	13.0	- Includes 1.0 liter which
850	12.0	12.0	12.0	12.0	12.0	was pH adjusted to 5-6 range
851	9.0	12.0	9.0	12.0	25.0	through addition of Na2CO3
852	9.0	12.0	9.0	12.0	25.0	(150 g/L solution) and recycled
853	9.0	12.0	9.0	12.0	25.0	as part of 16th seeding mixture
854	9.0	12.0	9.0	12.0	25.0	
855	9.0	12.0	9.0	12.0	25.0	
856	10.0	13.0	10.0	13.0	1.0	- Includes 1.0 liter which
857	9.0	12.0	9.0	12.0	0.0	was pH adjusted to 5-6 range
858	9.0	12.0	9.0	12.0	0.0	through addition of Na2CO3
859	12.0	12.0	12.0	12.0	12.0	(150 g/L solution) and recycled

Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	Notes
860	12.0	12.0	12.0	12.0	12.0	as part of 17th seeding mixture
861	12.0	12.0	12.0	12.0	12.0	
862	12.0	12.0	12.0	12.0	12.0	
863	13.0	13.0	13.0	13.0	13.0	- Includes 1.0 liter which
864	12.0	12.0	12.0	12.0	12.0	was pH adjusted to 5-6 range
865	12.0	12.0	12.0	12.0	12.0	through addition of Na2CO3
866	12.0	12.0	12.0	12.0	12.0	(150 g/L solution) and recycled
867	12.0	12.0	12.0	12.0	12.0	as part of 18th seeding mixture
868	12.0	12.0	12.0	12.0	12.0	
869	12.0	12.0	12.0	12.0	12.0	
870	13.0	13.0	13.0	13.0	13.0	- Includes 1.0 liter which
871	12.0	12.0	12.0	12.0	12.0	was pH adjusted to 5-6 range
872	12.0	12.0	12.0	12.0	12.0	through addition of Na2CO3
873	12.0	12.0	12.0	12.0	12.0	(150 g/L solution) and recycled
874	12.0	12.0	12.0	12.0	12.0	as part of 19th seeding mixture
875	12.0	12.0	12.0	12.0	12.0	
876	12.0	12.0	12.0	12.0	12.0	
877	13.0	13.0	13.0	13.0	13.0	- Includes 1.0 liter which
878	12.0	12.0	12.0	12.0	12.0	was pH adjusted to 5-6 range
879	12.0	12.0	12.0	12.0	12.0	through addition of Na2CO3
880	12.0	12.0	12.0	12.0	12.0	(150 g/L solution) and recycled
881	12.0	12.0	12.0	12.0	12.0	as part of 20th seeding mixture
882	12.0	12.0	12.0	12.0	12.0	
883	12.0	12.0	12.0	12.0	12.0	
884	12.0	12.0	12.0	12.0	12.0	- 21st seeding, no leachate in mixture
885	12.0	12.0	12.0	12.0	12.0	
886	12.0	12.0	12.0	12.0	12.0	
887	12.0	12.0	12.0	12.0	12.0	
888	12.0	12.0	12.0	12.0	12.0	
889	12.0	12.0	12.0	12.0	12.0	
890	12.0	12.0	12.0	12.0	12.0	
891	12.0	12.0	12.0	12.0	12.0	- 22nd seeding
892	12.0	12.0	12.0	12.0	12.0	
893	12.0	12.0	12.0	12.0	12.0	
894	12.0	12.0	12.0	12.0	12.0	
895	12.0	12.0	12.0	12.0	12.0	
896	12.0	12.0	12.0	12.0	12.0	
897	12.0	12.0	12.0	12.0	12.0	
898	12.0	12.0	12.0	12.0	12.0	- 23rd and final seeding
899	12.0	12.0	12.0	12.0	12.0	
900	12.0	12.0	12.0	12.0	12.0	
901	12.0	12.0	12.0	12.0	12.0	
902	12.0	12.0	12.0	12.0	12.0	
903	12.0	12.0	12.0	12.0	12.0	
904	12.0	12.0	12.0	12.0	12.0	
905	12.0	12.0	12.0	12.0	12.0	
906	12.0	12.0	12.0	12.0	12.0	
907	12.0	12.0	12.0	12.0	12.0	
908	12.0	12.0	12.0	12.0	12.0	
909	12.0	12.0	12.0	12.0	12.0	
910	12.0	12.0	12.0	12.0	12.0	

Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	Notes
911	12.0	12.0	12.0	12.0	12.0	
912	12.0	12.0	12.0	12.0	12.0	
913	12.0	12.0	12.0	12.0	12.0	
914	12.0	12.0	12.0	12.0	12.0	
915	13.0	13.0	13.0	13.0	13.0	
916	8.0	8.0	8.0	8.0	8.0	- First day recycled quantity
917	9.0	9.0	9.0	9.0	9.0	limited by COL 6 leachate
918	8.0	8.0	8.0	8.0	8.0	production.
919	9.0	9.0	9.0	9.0	9.0	
920	8.0	8.0	8.0	8.0	8.0	
921	8.0	8.0	8.0	8.0	8.0	
922	6.0	6.0	6.0	6.0	6.0	
923	6.2	6.2	6.2	6.2	6.2	
924	6.5	6.5	6.5	6.5	6.5	
925	6.0	6.0	6.0	6.0	6.0	
926	6.0	6.0	6.0	6.0	6.0	
927	7.0	7.0	7.0	7.0	7.0	
928	6.0	6.0	6.0	6.0	6.0	
929	5.0	5.0	5.0	5.0	5.0	
930	6.0	6.0	6.0	6.0	6.0	
931	4.5	4.5	4.5	4.5	4.5	
932	5.0	5.0	5.0	5.0	5.0	
933	5.0	5.0	5.0	5.0	5.0	
934	3.0	3.0	3.0	3.0	3.0	
935	5.0	5.0	5.0	5.0	5.0	
936	3.0	3.0	3.0	3.0	3.0	
937	4.0	4.0	4.0	4.0	4.0	
938	3.0	3.0	3.0	3.0	3.0	
939	3.0	3.0	3.0	3.0	3.0	
940	3.0	3.0	3.0	3.0	3.0	
941	3.0	3.0	3.0	3.0	3.0	
942	3.0	3.0	3.0	3.0	3.0	
943	2.0	2.0	2.0	2.0	2.0	
944	2.5	2.5	2.5	2.5	2.5	
945	3.0	3.0	3.0	3.0	3.0	
946	2.5	2.5	2.5	2.5	2.5	
947	3.0	3.0	3.0	3.0	3.0	
948	2.8	2.8	2.8	2.8	2.8	
949	2.5	2.5	2.5	2.5	2.5	
950	3.0	3.0	3.0	3.0	3.0	
951	2.5	2.5	2.5	2.5	2.5	
952	2.5	2.5	2.5	2.5	2.5	
953	2.0	2.0	2.0	2.0	2.0	
954	2.5	2.5	2.5	2.5	2.5	
955	3.0	3.0	3.0	3.0	3.0	
956	2.0	2.0	2.0	2.0	2.0	
957	2.5	2.5	2.5	2.5	2.5	
958	2.0	2.0	2.0	2.0	2.0	
959	2.8	2.8	2.8	2.8	2.8	
960	2.0	2.0	2.0	2.0	2.0	
961	2.2	2.2	2.2	2.2	2.2	

Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	Notes
1013	2.0	2.0	2.0	2.0	2.0	
1014	2.0	2.0	2.0	2.0	2.0	
1015	1.8	1.8	1.8	1.8	1.8	
1016	2.0	2.0	2.0	2.0	2.0	
1017	2.0	2.0	2.0	2.0	2.0	
1018	2.0	2.0	2.0	2.0	2.0	
1019	1.8	1.8	1.8	1.8	1.8	
1020	1.8	1.8	1.8	1.8	1.8	
1021	1.2	1.2	1.2	1.2	1.2	
1022	1.5	1.5	1.5	1.5	1.5	
1023	1.0	1.0	1.0	1.0	1.0	
1024	1.8	1.8	1.8	1.8	1.8	
1025	1.8	1.8	1.8	1.8	1.8	
1026	0.0	0.0	0.0	0.0	0.0	
1027	1.5	1.5	1.5	1.5	1.5	
1028	1.8	1.8	1.8	1.8	1.8	
1029	1.0	1.0	1.0	1.0	1.0	
1030	2.0	2.0	2.0	2.0	2.0	
1031	1.0	1.0	1.0	1.0	1.0	
1032	1.5	1.5	1.5	1.5	1.5	
1033	2.0	2.0	2.0	2.0	2.0	
1034	2.0	2.0	2.0	2.0	2.0	
1035	2.0	2.0	2.0	2.0	2.0	
1036	2.0	2.0	2.0	2.0	2.0	
1037	2.0	2.0	2.0	2.0	2.0	
1038	1.8	1.8	1.8	1.8	1.8	
1039	2.0	2.0	2.0	2.0	2.0	
1040	1.0	1.0	1.0	1.0	1.0	
1041	1.5	1.5	1.5	1.5	1.5	
1042	2.0	2.0	2.0	2.0	2.0	
1043	1.0	1.0	1.0	1.0	1.0	
1044	1.5	1.5	1.5	1.5	1.5	
1045	0.0	0.0	0.0	0.0	0.0	
1046	3.0	3.0	3.0	3.0	3.0	
1047	0.0	0.0	0.0	0.0	0.0	
1048	1.0	1.0	1.0	1.0	1.0	
1049	1.5	1.5	1.5	1.5	1.5	
1050	1.0	1.0	1.0	1.0	1.0	
1051	2.0	2.0	2.0	2.0	2.0	
1052	1.5	1.5	1.5	1.5	1.5	
1053	1.0	1.0	1.0	1.0	1.0	
1054	1.0	1.0	1.0	1.0	1.0	
1055	1.5	1.5	1.5	1.5	1.5	
1056	2.0	2.0	2.0	2.0	2.0	
1057	1.5	1.5	1.5	1.5	1.5	
1058	1.5	1.5	1.5	1.5	1.5	
1059	1.0	1.0	1.0	1.0	1.0	
1060	0.0	0.0	0.0	0.0	0.0	
1061	2.5	2.5	2.5	2.5	2.5	
1062	1.5	1.5	1.5	1.5	1.5	
1063	2.0	2.0	2.0	2.0	2.0	First day started recycling every 2nd day

Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	Notes
1064	0.0	0.0	0.0	0.0	0.0	
1065	3.0	3.0	3.0	3.0	3.0	
1066	0.0	0.0	0.0	0.0	0.0	
1067	0.0	0.0	0.0	0.0	0.0	
1068	0.0	0.0	0.0	0.0	0.0	
1069	5.0	5.0	5.0	5.0	5.0	
1070	0.0	0.0	0.0	0.0	0.0	
1071	3.0	3.0	3.0	3.0	3.0	
1072	0.0	0.0	0.0	0.0	0.0	
1073	3.5	3.5	3.5	3.5	3.5	
1074	0.0	0.0	0.0	0.0	0.0	
1075	3.0	3.0	3.0	3.0	3.0	
1076	0.0	0.0	0.0	0.0	0.0	
1077	4.0	4.0	4.0	4.0	4.0	
1078	0.0	0.0	0.0	0.0	0.0	
1079	3.0	3.0	3.0	3.0	3.0	
1080	0.0	0.0	0.0	0.0	0.0	
1081	3.0	3.0	3.0	3.0	3.0	
1082	0.0	0.0	0.0	0.0	0.0	
1083	3.0	3.0	3.0	3.0	3.0	
1084	0.0	0.0	0.0	0.0	0.0	
1085	2.5	2.5	2.5	2.5	2.5	
1086	0.0	0.0	0.0	0.0	0.0	
1087	3.0	3.0	3.0	3.0	3.0	
1088	0.0	0.0	0.0	0.0	0.0	
1089	0.0	0.0	0.0	0.0	0.0	
1090	2.5	2.5	2.5	2.5	2.5	
1091	0.0	0.0	0.0	0.0	0.0	
1092	2.0	2.0	2.0	2.0	2.0	
1093	0.0	0.0	0.0	0.0	0.0	
1094	3.0	3.0	3.0	3.0	3.0	
1095	0.0	0.0	0.0	0.0	0.0	
1096	2.5	2.5	2.5	2.5	2.5	
1097	0.0	0.0	0.0	0.0	0.0	
1098	2.0	2.0	2.0	2.0	2.0	
1099	0.0	0.0	0.0	0.0	0.0	
1100	3.0	3.0	3.0	3.0	3.0	
1101	0.0	0.0	0.0	0.0	0.0	
1102	3.0	3.0	3.0	3.0	3.0	
1103	0.0	0.0	0.0	0.0	0.0	
1104	3.0	3.0	3.0	3.0	3.0	
1105	0.0	0.0	0.0	0.0	0.0	
1106	3.0	3.0	3.0	3.0	3.0	
1107	0.0	0.0	0.0	0.0	0.0	
1108	2.5	2.5	2.5	2.5	2.5	
1109	0.0	0.0	0.0	0.0	0.0	
1110	0.0	0.0	0.0	0.0	0.0	
1111	2.0	2.0	2.0	2.0	2.0	
1112	0.0	0.0	0.0	0.0	0.0	
1113	1.5	1.5	1.5	1.5	1.5	
1114	0.0	0.0	0.0	0.0	0.0	

Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	Notes
1115	1.0	1.0	1.0	1.0	1.0	
1116	0.0	0.0	0.0	0.0	0.0	
1117	1.0	1.0	1.0	1.0	1.0	
1118	0.0	0.0	0.0	0.0	0.0	
1119	1.0	1.0	1.0	1.0	1.0	First day started recycle every fourth day
1120	0.0	0.0	0.0	0.0	0.0	
1121	0.0	0.0	0.0	0.0	0.0	
1122	0.0	0.0	0.0	0.0	0.0	
1123	2.0	2.0	2.0	2.0	2.0	
1124	0.0	0.0	0.0	0.0	0.0	
1125	0.0	0.0	0.0	0.0	0.0	
1126	0.0	0.0	0.0	0.0	0.0	
1127	2.0	2.0	2.0	2.0	2.0	
1128	0.0	0.0	0.0	0.0	0.0	
1129	0.0	0.0	0.0	0.0	0.0	
1130	0.0	0.0	0.0	0.0	0.0	
1131	0.0	0.0	0.0	0.0	0.0	
1132	0.5	0.5	0.5	0.5	0.5	

APPENDIX II

Seeding Summary

"Seed" - a mixture of anaerobic digester effluent, water and sometimes leachate. In some instances the pH of the leachate was raised through the addition of Na_2CO_3 (150 g/L solution).

The anaerobic digester sludge was collected from the R. M. Clayton wastewater treatment plant, Atlanta, GA, and had the following characteristics:

pH = 7.9
Alkalinity = 3.1 g/L as $CaCO_3$
Solids = 2.5 %
Volatile solids = 60 %

Seeding No.	Date (Days Since Loading)	Digester sludge (liters)	Tap water (liters)	Leachate (liters)	Total Volume Added (liters)	NOTES:
1	16 Jul 87 (666)	5	1	0	6	
2	03 Aug 87 (684)	5	1	0	6	
3	21 Aug 87 (702)	5	1	0	6	
4	11 Sep 87 (723)	5	1	0	6	
5	28 Sep 87 (740)	5	1	0	6	
6	07 Oct 87 (749)	5	1	0	6	
7	19 Oct 87 (761)	5	1	0	6	
8	28 Oct 87 (770)	5	1	0	6	
9	02 Nov 87 (775)	4	1	1	6	- pH of leachate adjusted to 6-7 through addition of Na_2CO_3 (150 g/L solution)
10	19 Nov 87 (792)	2	3	1	6	- pH of leachate adjusted to 6-7 through addition of 25 mLs Na_2CO_3 (150 g/L solution)
11	01 Dec 87 (804)	4	1	1	6	" " " "
12	10 Dec 87 (813)	4	1	1	6	" " " "
13	19 Dec 87 (822)	4	1	1	6	" " " "
14	30 Dec 87 (833)	4	1	1	6	" " " "
15	08 Jan 88 (842)	4	1	1	6	" " " "
		3	1	2	6	- same except 50 mLs Na_2CO_3 added
16	15 Jan 88 (849)	4	1	1	6	- pH of leachate adjusted to 6-7 through addition of 25 mLs Na_2CO_3 (150 g/L solution)
17	22 Jan 88 (856)	4	1	1	6	" " " "
18	29 Jan 88 (863)	4	1	1	6	" " " "
19	05 Feb 88 (870)	4	1	1	6	" " " "
20	12 Feb 88 (877)	4	1	1	6	" " " "
21	19 Feb 88 (884)	5	1	0	6	
22	26 Feb 88 (891)	5	1	0	6	
23	04 Mar 88 (898)	5	1	0	6	

APPENDIX III

Column 1 Gas Composition (%)

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
21	64	2	52		0	100	0
25	37	0	45				
30	40	0	34	10.5			
35	42	1	38				
36				6.1			
44	51	0	35				
53				3.1			
63	64	1	29				
64				2.4			
88	54	4	34	2.5			
103	60	1	27				
109				0.6			
121					0		
129	47	4	37				
143	45	5	36				
179	56	2	38	2.4	1	98	2
187				2.0	0		
220	79	3	27	1.4	0	100	0
246	69	0	21	1.4	0	100	0
253							
284	86	1	21				
300	77	0	21				
302				3.4	0		
310	58	1	18				
315				1.3	0		
340	78	0	13				
408	72	1	25	3.0	1	99	1
429	51	1	47		0	100	0
475	61	1	35	0.5	0	100	0
508							
518	50	3	43		0	100	0
548	60	1	40	1.5	0	100	0
601	36	1	62		0	100	0
630	41	0	51	0.5	0	100	0
680	47	0	49				
695		1	73	0.2	0		
731				1.5	5		
748				1.5	6		
755				1.2	7		
756							
762					13		
766				1.8	12		
782					26		
787					30		
796			47				

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
797				1.1	40		
804				0.6	44		
810				0.4	42		
834	41		4	0.0	45	48	52
844	43		2		60	42	58
850	43				58	43	57
862	47		2		56	46	54
871	42	0	0		59	42	58
879	42	0	2		56	43	57
891	40		3		55	42	58
901	45		2		53	46	54
917	44		1		58	43	57
943	46		1	0.0	55	46	54
965	44	1	1	0.0	50	47	53
1008	42	0	2		56	43	57
1016	40	0	0		62	39	61
1025	38	0	1		57	40	60
1035	42	0	2		56	43	57
1051	43	0	0		59	42	58
1059	42	0	1		59	42	58
1071				0.0			
1077	42	0	1		59	42	58
1087	43	0	0		60	42	58
1094	43	0	1		59	42	58
1101	43	0	1		56	43	57
1102				0.0			
1108	42	0	1		55	43	57
1114	41	0	1		56	42	58
1115				0.0			
1128	36	0	2		55	40	60

[illegible]

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
797				1.1	37		
804				0.9	36		
810				0.8	40		
834	45		9	0.8	45	50	50
844	47		5		44	52	48
850	46		7		46	50	50
862	51		6		45	53	47
871	44	0	4		46	49	51
879	46	0	4		46	50	50
891	43		6		47	48	52
901	49		4		46	52	48
917	47		2		54	47	53
943	49	0	1	0.0	47	51	49
965	48	1	2	0.2	47	51	49
1008	47	0	3	0.0	50	48	52
1016	37	0	0		57	39	61
1025	42	0	2		54	44	56
1035	45	0	2		53	46	54
1051	44	0	2		56	44	56
1059	45	0	2		56	45	55
1071				0.0			
1077	45	0	1		58	44	56
1087	45	0	1		58	44	56
1094	41	0	2		55	43	57
1101	40	0	1		55	42	58
1102				0.0			
1108	45	0	1		58	44	56
1114	35	0	15		48	42	58
1115				0.0			
1128	43	0	4		60	42	58

[illegible]

Column 3 Gas Composition (%)

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
21	29	2	52		0	100	0
25	36	0	51				
30	40	0	34	6.6			
35	45	0	32				
36				7.7			
44							
53				1.2			
63	61	0	32				
64				1.4			
88	58	1	33	4.6			
103	53	1	31				
109				0.9			
121					0		
129	54	0	29				
143	52	1	29				
179	57	2	48	1.6	0	100	0
187				1.1	0		
220	21	12	69	0.1	0	100	0
246	29	0	68	0.3	0	100	0
253							
284	24	11	71				
300	50	0	48				
302			34	2.8	0		
310	49	0	34				
315				1.4	0		
340	50	0	35		0	100	0
408	53	1	45	0.0	0	100	0
429	67	1	31	0.0	0	100	0
475	41	1	48	0.0	0	100	0
508		0					
518	41		55	0.0	0	100	0
548	40	1	64	0.0	0	100	0
601	35	0	64	0.0	0	100	0
630	42	0	53	0.0	0	100	0
680	47	0	42		0	100	0
695		1	63	0.4	0		
731				1.8	3		
748				0.9	4		
755				0.5	2		
756							
762				2.0	7		
766				1.6	6		
782					8		
787					8		
796			49				
797				1.5	10		
804					11		

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
810					12		
834	49		36	1.0	17	74	26
844	43		36		18	70	30
850	45		31		20	69	31
862	44		29		21	68	32
871	42	1	28		24	64	36
879	44	0	22		26	63	37
891	46		20		27	63	37
901	46		17		29	61	39
917	44		22		30	59	41
943	44		22		29	60	40
965	46	1	11	0.8	28	62	38
1008	46	0	20	0.0	34	58	43
1016	40	0	22		39	51	49
1025	41	0	23		38	52	48
1035	44	0	18		40	52	48
1051	42	0	16		39	52	48
1059	40	0	18		42	49	51
1071				0.1			
1077	44	0	14		43	51	49
1087	39	0	22		39	50	50
1094	17	8	55		14	55	45
1101	42	0	18		40	51	49
1102				1.2			
1108	39	0	26		38	51	49
1114	27	0	46		27	50	50
1115				0.7			
1128	34	0	37		35	49	51

Column 4 Gas Composition (%)

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
21	55	2	56		0	100	0
25	31	3	53				
30	37	0	43	9.6			
35	36	0	33				
36				1.4			
44	47	0	34				
53				3.9			
63	57	1	34				
64				3.0			
88	50	1	38	4.7			
103	47	1	40				
109				3.0			
121					0		
129	42	2	48				
143	41	3	47				
179	25	3		2.7	0	99	1
187				0.3	0		
220	38	2	63	0.5	0	100	0
246	29	0	57	0.3	0	100	0
253							
284	37	2	63				
300	47	0	57				
302			38	6.7	0		
310	49	0	35				
315				6.8	0		
340	43	0	33				
408	50	1	43	2.3	0	100	0
429	55	1	42		0	100	0
475	57	1	39	3.0	0	100	0
508							
518	47	0	47		0	100	0
548	50	0	52	2.0	0	100	0
601	45	0	53		0	100	0
630	47	0	49	2.3	0	100	0
680	45	0	50		0	100	0
695		0	64	1.4	0		
731				1.9	2		
748				0.9	2		
755				0.9	2		
756							
762				1.5	3		
766				1.5	3		
782					6		
787					5		
796			59				
797					8		
804					8		

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
810					9		
834	36		42	1.8	14	72	28
844	38		42		15	72	28
850	39		38		19	67	33
862	43		33		20	68	32
871	40	1	28		22	65	35
879	46	0	25		25	65	35
891	44		25		25	64	36
901	42		20		26	62	38
917	42		28		28	60	40
943	43		32	0.0	26	62	38
965	45		20	1.0	25	64	36
1008	43		28		26	62	38
1016	37	0	39		29	56	44
1025	37	0	40		29	56	44
1035	39	0	31		31	56	44
1051	37	0	30		33	53	47
1059	39	0	32		34	53	47
1071				0.2			
1077	38	0	26		34	53	47
1087	28	0	45		23	55	45
1094	35	0	32		31	53	47
1101	39	0	30		33	54	46
1102				0.1			
1108	39	0	34		33	54	46
1114	33	0	38		29	53	47
1115				0.1			
1128	36	0	44		33	52	48

Column 5 Gas Composition (%)

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
21	55	2	59		0	100	0
25	36	0	48				
30	39	0	44				
35	37	0	37				
36				1.2			
44	45	0	39				
53				3.0			
63	59	1	39				
64				1.4			
88	49	1	42	3.4			
103	46	2	42				
109				0.6			
121					0		
129	47	1	40				
143	45	2	39				
179	54	3	55	3.2	0	99	1
187				2.2	0		
220	70	3	34	1.2	0	100	0
246	56	1	34	0.9	0	99	1
253							
284	62	4	39				
300	76	0	30				
302			21	3.0	0		
310	73	0	18				
315				1.2	0		
340	63	0	22				
408	57	1	38	1.5	0	100	0
429	55	1	53		0	100	0
475	54	1	41	0.0	0	100	0
508							
518	30	4	55		0	100	0
548	48	0	55	1.0	0	100	0
601	40	0	62		0	100	0
630	40	0	56	1.8	0	100	0
680	52	0	40		0	100	0
695		0	58	1.0	0		
731				1.9	2		
748				0.6	1		
755				1.1			
756					3		
762				1.8	4		
766				1.2	4		
782					6		
787					6		
796			49				
797					8		
804					8		

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
810					10		
834	44		36	1.2	13	77	23
844	45		37		14	76	24
850	45		35		16	74	26
862	50		31		18	74	26
871	46	1	30		19	71	29
879	45	0	23		23	66	34
891	44		24		23	66	34
901	44		19		24	65	35
917	42		29		27	61	39
943	42		31		24	64	36
965	43	0	22	0.8	22	66	34
1008	44		28		24	65	35
1016	38	0	37		26	59	41
1025	38	0	39		27	58	42
1035	39	0	33		30	57	43
1051	36	0	38		26	58	42
1059	37	0	37		28	57	43
1071				0.1			
1077	41	0	31		32	56	44
1087	36	0	38		25	59	41
1094	36	0	35		27	57	43
1101	36	0	39		26	58	42
1102				0.1			
1108	35	0	40		25	58	42
1114	35	0	42		25	58	42
1115				0.1			
1128	34	0	56		26	57	43

Column 6 Gas Composition (%)

Days Since Loading	CO_2	O_2	N_2	H_2	CH_4	CO_2 (%):CH_4 (%)	
21	53	2	53	12.2	0	100	0
25	31	0	48				
30	36	0	40				
35	38	0	37				
36				8.3			
44	49	0	35				
53				5.0			
63	64	1	29				
64				3.7			
88	55	1	34	5.2			
103	53	1	40				
109				1.0			
121					0		
129	47	0	35				
143	46	1	34				
179	55	0	50	4.5	0	99	1
187				8.8	1		
220	71	1	30	4.7	0	100	0
246	57	1	31	4.1	0	100	0
253							
284	66	1	26				
300	60	3	27				
302			27	7.8	0		
310	64	0	13				
315				7.7	0		
340	61	0	18				
408	60	1	27	2.3	0	100	0
429	53	1	40		0	100	0
475	43	1	51	0.5	0	100	0
508							
518							
548	56	1	40	1.0	0	100	0
601	35	0	64		0	100	0
630	39	0	60	0.2	0	100	0
680	53	0	39		0	100	0
695		0	60	1.3	0		
731				1.7	1		
748				0.7	1		
755							
756							
762				1.8	4		
766				1.2	3		
782					4		
787					4		
796			56				
797				1.3	7		
804				1.2	11		

[illegible]

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
810				1.2	13		
834	40		24	0.5	30	57	43
844	40		24		38	51	49
850	41		18		46	47	53
862	43		11		48	47	53
871	42	0	6		52	45	55
879	42	0	4		55	43	57
891	43		2		55	44	56
901	46		2		54	46	54
917	44		1		57	44	56
943	46		1		52	47	53
965	43	0	1	0.1	50	46	54
1008	42	0	4	0.0	55	43	57
1016	42	0	0		60	41	59
1025	41	0	1		56	42	58
1035	43	0	1		56	43	57
1051	42	0	2		58	42	58
1059	42	0	1		58	42	58
1071				0.0			
1077	43	0	2		57	43	57
1087	43	0	0		57	43	57
1094	42	0	2		59	42	58
1101	41	0	2		55	43	57
1102				0.0			
1108	41	0	2		56	42	58
1114	43	0	2		55	44	56
1115				0.0			
1128	43	0	3		61	41	59

Column 7 Gas Composition (%)

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
21	21	11	68		0	100	0
25	35	1	52				
30	39	0	43	6.6			
35	38	0	34				
36				11.6			
44	50	0	39				
53				1.9			
63	53	3	40				
64				2.0			
88	49	1	41	3.2			
103	46	2	41				
109				0.7			
121					0		
129	34	1	41				
143	36	3	43				
179	39	4	69	2.5	0	99	1
187				1.5	0		
220	48	3	53	0.9	0	100	0
246	37	3	52				
253				7.4	0		
284	44	3	43				
300	60	0	40				
302			37	9.7	0		
310	55	0	20				
315				9.5	1		
340	48	0	23				
408	42	1	40	2.0	0	100	0
429	58	1	39		0	100	0
475	56	1	40	1.5	0	100	0
508							
518							
548							
601	41	0	58		0	100	0
630	40		57	0.9	0	100	0
680	40	1	59		0	100	0
695		1	74	1.0	0		
731					1		
748				1.3	2		
755				1.2	3		
756							
762					5		
766					4		
782					8		
787					11		
796			63				
797					19		
804					27		

[illegible]

[illegible]

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
810					34		
834	44		16	0.6	38	54	46
844	41		10		50	45	55
850	38		10		53	42	58
862	43		5		54	44	56
871	42	0	2		54	44	56
879	41	0	2		55	43	57
891	43		2		55	44	56
901	46		2		53	46	54
917	43		1		54	44	56
943	46		1		52	47	53
965	47	0	2	0.1	46	51	49
1008	46	0	1	0.0	53	46	54
1016	43	0	0		60	42	58
1025	42	0	2		55	43	57
1035	44	0	1		57	44	56
1051	44	0	2		58	43	57
1059	42	0	2		60	41	59
1071				0.0			
1077	44	0	2		57	44	56
1087	42	0	1		60	41	59
1094	40	0	2		60	40	60
1101	40	0	1		56	42	58
1102				0.0			
1108	41	0	0		56	42	58
1114	41	0	1		57	42	58
1115				0.0			
1128	41	0	3		58	41	59

Column 8 Gas Composition (%)

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
21	62	3	59		0	100	0
25	35	2	50				
30	39	0	43	9.4			
35	32	0	32				
36				12.3			
44	50	0	34				
53				2.0			
63	60	1	35				
64				1.6			
88	50	1	39	3.0			
103	48	1	40				
109				1.8			
121					0		
129	34	3	43				
143	36	5	44				
179	44	5	59	2.7	0	99	1
187				1.0	0		
220	15	17	78	0.1	0	100	0
246	16	15	71				
253				0.0	0		
284	0	20	80				
300	0	17	74				
302			67	0.0	0		
310	49	0	36				
315				5.0	0		
340	48	0	30				
408	47	1	45	0.0	2	95	5
429	40	1	49		0	100	0
475	66	1	32	1.5	0	100	0
508							
518	48	2	51		0	100	0
548	48	2	49	1.0	0	100	0
601	45	0	53		0	100	0
630	51	0	46		0	100	0
680	57	0	38		0	100	0
695		0	40		0		
731				1.8	2		
748				1.0	2		
755				1.2	3		
756							
762				2.0	3		
766				2.0	3		
782					7		
787					7		
796			52				
797				2.0	10		
804				1.6	12		

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
810				1.8	15		
834	44		38	0.8	14	76	24
844	49		33		18	73	27
850	46		29		21	69	31
862	48		24		21	70	30
871	44	0	20		22	67	33
879	49	0	17		28	64	36
891	48		19		28	63	37
901	47		15		30	61	39
917	45		18		31	59	41
943	48		10		31	61	39
965	48	1	20	0.7	22	69	31
1008	50	0	16	0.0	35	59	41
1016	47	0	16		39	55	45
1025	45	0	19		35	56	44
1035	48	0	16		37	56	44
1051	48	0	13		42	53	47
1059	47	0	14		42	53	47
1071				0.1			
1077	48	0	12		42	53	47
1087	42	0	21		36	54	46
1094	37	0	25		33	53	47
1101	46	0	13		42	52	48
1102				0.1			
1108	43	0	18		38	53	47
1114	32	0	36		28	53	47
1115				0.0			
1128	42	0	21		39	52	48

Column 9 Gas Composition (%)

Days Since Loading	CO_2	O_2	N_2	H_2	CH_4	CO_2 (%):CH_4 (%)	
21	37	6	63		0	100	0
25	34	2	53				
30	39	0	45	8.4			
35	40	0	34				
36				1.1			
44	25	10	58				
53				1.5			
63	53	1	34				
64				1.3			
88	49	2	44	2.4			
103	48	1	43				
109				0.5			
121					0		
129	41	1	36				
143	43	3	39				
179	46	3	64	1.3	0	99	1
187				1.0	0		
220		21	78	0.6	0		
246	46	1	46				
253				1.2	0		
284	61	2	38				
300	64	0	33				
302			29	7.5	0		
310	65	0	20				
315				10.4	0		
340	52	0	17				
408	50	1	45	5.0	0	100	0
429	57	1	38		0	100	0
475	48	1	49	2.0	0	100	0
508							
518	50	1	46		0	100	0
548	52	0	49	1.5	0	100	0
601	37	0	63		0	100	0
630	43	0	54	1.2	0	100	0
680	50	0	38		0	100	0
695		0	60	1.6	0		
731				1.8	1		
748				0.8	1		
755				1.0	1		
756							
762				1.8	3		
766				1.3	3		
782					4		
787					5		
796			66				
797				1.3	9		
804				1.2	15		

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
810				1.0	17		
834	48		25	0.5	35	58	42
844	43		19		43	50	50
850	41		15		48	46	54
862	43		8		51	46	54
871	42	0	3		55	43	57
879	46	0	3		56	45	55
891	41		3		58	41	59
901	44		2		55	44	56
917	42		1		60	41	59
943	45		1		53	46	54
965	46	0	1	0.0	48	49	51
1008	48	0	1		51	48	52
1016	44	0	0		56	44	56
1025	45	0	1		57	44	56
1035	48	0	1		55	47	53
1051	46	0	2		56	45	55
1059	43	0	1		56	43	57
1071				0.0			
1077	43	0	2		62	41	59
1087	36	0	2		57	39	61
1094	40	0	1		60	40	60
1101	40	0	2		55	42	58
1102				0.0			
1108	42	0	1		58	42	58
1114	38	0	2		56	40	60
1115				0.0			
1128	40	0	3		58	41	59

Column 10 Gas Composition (%)

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
21	53	2	60		0	100	0
25	30	4	57				
30	37	0	47	8.3			
35	34	0	34				
36				1.2			
44	47	0	42				
53				1.3			
63	23	1	61				
64				0.9			
88	47	2	44	1.3			
103	48	1	43				
109				0.1			
121					0		
129	40	0	36				
143	42	2	37				
179	41	4	54	2.9	0	99	1
187				2.1	1		
220	56	2	44	0.6	0	100	0
246	46	6	55				
253				1.6	0		
284	18	14	71				
300	46	11	67				
302			38	7.1	0		
310	50	0	31				
315				7.3	0		
340	43	0	40			100	0
408	37	1	43	2.0	0	100	0
429	62	1	35		0	100	0
475	49	1	44	1.2	0	100	0
508							
518							
548	37	0	63	1.0	0	100	0
601	38	0	60		0	100	0
630	45	0	52	0.3	0	100	0
680	36	0	53		0	100	0
695		1	71	1.4	0		
731				2.2	1		
748				0.8	1		
755				1.8	3		
756							
762				1.5	4		
766				1.2	4		
782					6		
787					8		
796			63				
797				2.2	12		
804				2.0	20		

Days Since Loading	CO2	O2	N2	H2	CH4	CO2 (%):CH4 (%)	
810				1.9	25		
834	35		23	0.8	42	45	55
844	39		18		47	45	55
850	40		16		51	44	56
862	42		9		51	45	55
871	41	0	4		52	44	56
879	41	0	5		56	42	58
891	40		4		55	42	58
901	40		2		57	41	59
917	46		1		63	42	58
943	47	0	1		56	46	54
965	43	0	1	0.1	53	45	55
1008	42	0	2		57	42	58
1016	42	0	0		59	42	58
1025	39	0	1		59	40	60
1035	45	0	2		59	43	57
1051	42	0	2		58	42	58
1059	42	0	1		59	42	58
1071				0.0			
1077	43	0	2		56	43	57
1087	43	0	1		57	43	57
1094	40	0	5		55	42	58
1101	43	0	2		57	43	57
1102				0.0			
1108	43	0	1		56	43	57
1114	38	0	7		52	42	58
1115				0.0			
1128	42	0	2		59	42	58

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APPENDIX IV

Leachate Chemical Oxygen Demand Concentration (mg/L)

Days Since Loading	Recycle Columns					Single Pass Columns				
	COL 1	COL 6	COL 7	COL 9	COL 10	COL 2	COL 3	COL 4	COL 5	COL 8
50	87650	41450	41450	51200	54000	22700	48600	65000	67000	73000
69	82990	50230	46800	45860	52420	35670	59700	68400	41400	73530
85	64790	61150	64060	40040	45140	26210	64060	88820	58970	77170
92	72600	61200	60600	33600	61800	48000	64800	84600	55200	71400
99	83330	69330	60000	36000	66000	37330	61330	69000	54000	73330
106	69330	64665	56000	34000	62000	37330	56330	72000	53330	69330
114	64000	66670	58670	43330	64000	40000	57335	82000	60000	72330
122	61575	61575	52170	37610	57030	38830	55210	74010	57030	69770
135	54600	53400	44400	37200	55800	27300	41400	55800	51300	70200
148	63000	57600	49800	38700	60600	33000	52200	73200	57300	78000
170	60320	63090	52690	42290	51800	44370	47150	60000	47150	79730
185	55000	55330	54340	52000	60330	40670	42000	45300	48000	53180
204	48970	47990	51880	47640	58370	29830	29830	38260	39560	42600
219	42000	43210	48800	41000	54900	22000	26540	33950	42600	39300
232	45000	48800	57000	43100	57000		28500	34500	31000	41300
248	45000	50000	48670	44000	58670		25300	30000	31300	46450
254	40880	32820	45210	45830	62550		24770	29110	23530	42400
268	55000	57000	57000	52000	70000	40000	36000	29000	34000	37000
282	50000	52100	54000	47000	62400	38000	28000	30000	28400	38000
296	53150	52000	57500	54000	61000	42000	30000	29600	30000	42350
317	55400	59880	57610	55400	62210	43220	36000	35260	37460	35800
333	59700	62500	57650	55600	66850	32000	30000	27000	25000	29625
345	53250	61400	39000	46500	44650	33350	25475	17600	27000	23950
363	48350	54150	49350	52850	58050	38750	19500	21350	23000	24500
378	61000	59000	50000	48750	59750	31000	30400	19350	25100	22600
390	55850	56550	52750	47250	58750	29250	20300	17000	24150	16406
408	63188	60844	56213	56275	68063	20709	15100	13200	18463	20588
429	59300	56825	46488	54425	62200	19650	18325	16325	22700	24188
450	57938	56078	44532	65625	65813	21856	19313	15644	23250	19688
471	55125	54000	53156	52594	56625	20062	18563	15047	18000	20625
499	44155	48188	45375	44250	47250	20062	17625	13312	21188	18200
540	55100	54200	45600	48900	53800	21200	18300	15500	14700	21800
561	50100	53600	47400	52700	53600	19000	20600	16800	20800	19500
582	50900	54600	41800	42000	47800	23400	20500	15100	19200	18800
603	46500	48000	36800	44200	50500	24800	20000	13800	17200	18600
624	53100		38200	43500		25400	19200	14400	19500	
645	51000	48000	49500		55000	27000	19500		12500	15500
666	48000	46000	47000	49500		23500	17500		12500	18000
687	48600	37300	37400	46400	43100	24400	17700	11500	11600	14800
733	61300	50200	49800	66900	61200	26500	20900	15200	33900	18200
754	55400	52700	48400	53800	54500	26000	23100	18500	31000	22400
775	52800	47600	46200	54100	54100	26500	22900	16000	19200	21700
796	60300	42100	49600	56700	54400	25600	20400	15700	34600	20200
818	47100	43900	43200	50300	54700	25300	22300	15900	18200	21700
838	45100	44000	37200	52800	46700	27400	25400	16200	18900	20700
859	40700	46200	32800	42000	45000	22700	22700	13900	20600	21600
880	36000	35700	51400	34500	36600	22200	22300	16300	18400	19700

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
901	31800	32700	21800	29700	38600	21900	21100	14800	17900	19900
922	24500	26700	19500	25000	31100	21700	21800	14800	18000	20300
943	21400	23300	19500	24000	28200	19100	20800	12500	14600	17900
964	25200	23600	23500	25800	28900	21800	21000	14300	18900	20600
985	22000	21300	22800	26000	30300	20900	21300	14400	17600	20100
1006	9100	19100	23000	28900	27700	20300	20900	14200	18600	19300
1027	1800	19800	23700	27100	26900	19200	21800	14400	18500	19500
1048	1957	24500	21400	26000	24800	17000	21200	16600	19000	19000
1069	1650	19100	19400	27700	27800	10200	22700	16500	20200	20700
1090	1300	13000	5300	9300	23000	3300	19100	9900	19800	16600
1111	2250	15000	7700	9400	25900	7200	21500	15000	19700	20400
1132	2500	15800	4900	23900	25700	6700	20600	13500	18800	19800

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APPENDIX V

Leachate Total Volatile Fatty Acids Concentration (mg/L as acetic acid)

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
51	9758	8184	7662	8396	7724	8432	7137	6664	5772	8396
58	11088	8564	8316	8355	8241	10117	7754	8155	7139	8355
67	13656	8638	9899	8373	8408	11570	7476	8219	10158	8373
88	5221	9477	8554	13930	9263	14844	8755	9548	9164	13930
92	19749	11284	8421	8854	8243	15713	9748	8959	8072	8854
100	19746	10081	8175	8164	8934	14712	8604	10182	7685	9343
108	21847	9955	7799	7897	8907	15820	8626	9609	7779	9013
123	21429	10495	9233	8763	9658	14905	8453	9978	8987	10459
135	23463	10293	9036	8966	8699	10453	10648	9318	8545	10693
148	21353	10697	9262	10499	10079	12817	13420	9666	9242	10917
170	20767	12765	9258	12636	10797	16065	12986	10292	10244	11714
198	19157	16440	10553	14585	15329	12455	12263	12488	13808	12124
204	19816	14572	10619	12538	14914	13186	10935		11754	
220	16310	14789	11107	13334	16929	11939	10136	11542	10753	12365
232	19030	15236	13159	13891	17444		9849	11388	11683	11924
248	17650	15532	14011	13155	18388		7821	8567	9033	11085
285	24745	22770	16333	19477	18003	9818	5624	8319	14058	24366
296	17464	14921	18369	24262		5819	16083	12771	15341	22696
310	20425	19074	15043	15893	19787	14884	12307	10464	11423	12442
331	13894	12167	10433	11779	13756	7940	7120	5643	6174	7816
363	13962	11640	8979	10995	10155	8418	5080	4863	5349	7137
390	15898	11983	10614	12832	14924	8107	5187	5022	6606	7514
428	15810	12456	9119	13113	14587	5532	3827	3824	6081	6194
449	16331	11820	10026	13465	13847	5391	3707	3082	4635	5822
467	15647	17113	14986	17196	19404	8149	5402	5402	6859	7114
495	18652	17427	9248	16618	13954	7939	5889	4448	6573	6999
537	18554	17477	13999	17044	19510	8594	6094	4829	6180	7640
551	20303	15880	14104	17654	18274	8633	7017	5262	7711	8024
572	17710	15546	13259	16524	18059	8304	6451	4658	6458	7238
644	19884	14936	14915	4356	18252	10967	6876	18601	6756	7471
699	21239	15990	15240	19537	19425	9069	5421	5587	6592	7445
753	28375	24990	20041	23303	23771	14817	12175	9621	12207	12888
774	24102	21123	17422	17720	18701	14712	8839	8262	8372	11607
797	8818							4166		
816	21404	19408	17752	21540	23706	12218	10603	9733	9319	11363
837	7825	7085	11778	17010	17833	5610	3836	4010	3617	7290
858	16172	14816	9996	14686		10172	8046	7873	8252	6751
879	23755	21760	13742	21621	25987	15498	12345	10423	11798	12232
900	12624	14440	7866	10686	13558	10227	8710	6404	7183	7451
922	13026	13815	10943	12828	15566	12172	11278	7009	8319	10984
943	12862	12693	12701	18997	16042	12762	9381	7652	7042	12135
964	11873	11485	11103	12097	12043	10444	8758	5860	7296	8761
985	10359	8772	9258	9981	10597	9274	8637	5868	8405	7444
1006	2952	13708	9285	14038	11446	7408	9463	7442	13721	7419
1027	8	6548	7588	10129	10914	6587	6780	4465	13794	7037
1048	25	8695	7438	12075	11774	6833	8969	6549	7874	7826

	Recycle Columns					Single Pass Columns				
Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	COL 2	COL 3	COL 4	COL 5	COL 8
1069	60	7202	7982	11128	11154	3538	10923	9262	14586	8001
1090	37		3332	3629	12852	1893	7539	5114		9387
1111	307	4096	1412	4027	9538	2880	8580	6120	8996	7610
1132	39	8487	600	7244	9393	4619	11938	10272	14066	12511

APPENDIX VI

Leachate Alkalinity (g/L as CaCO3)

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
85	12.10	8.20	11.20	11.30	11.20	7.00	8.70	9.70	8.60	16.10
98	12.60	9.30	10.20	5.80	9.30	7.10	9.20	13.10	8.90	13.30
105	15.70	9.70	9.40	1.71	9.70		10.70	13.50	9.10	14.00
119	16.95	14.30	9.40	8.10	15.30	9.20	13.70	10.40	7.30	19.60
127	17.40	11.30	9.40	9.40	10.80	9.40	11.20	13.40	11.00	15.00
139	15.10	10.60	9.10	10.30	10.90	8.10	12.50	10.90	10.30	14.20
178	12.30	11.00	8.60	6.80	3.40	13.40	12.40	13.20	13.20	12.80
222	10.49	13.20	9.70	10.90	15.40	6.70	8.47	8.60	10.20	10.50
245	11.40	14.50	14.50	6.00	17.70		8.01	8.50	8.50	10.00
284	11.73	13.69	13.16	11.60	15.90	9.06	7.55	6.91	7.30	8.99
287	12.38	14.53	14.01	10.75	15.64	8.79	8.15	8.80	8.15	9.45
303	12.38	13.10	12.64	12.70	15.31	8.80	7.49	6.45	7.43	9.12
313	12.60	14.30	11.60	12.80	17.27	8.80	7.17	6.84	7.82	8.40
330	12.77	13.82	11.50	13.40	16.60	8.28	6.13	5.93	6.91	8.02
342	12.10	13.70	9.32	13.00	15.80	7.89	5.93	5.80	6.78	7.75
356	11.70	13.20	10.30	13.20	16.00	6.40	5.70	5.30	7.10	7.40
370	12.10	13.40	11.20	13.20	16.60	7.00	5.30	5.10	6.60	6.80
385	13.00	13.20	11.70	13.80	16.40	5.90	4.70	4.60	6.60	6.70
398	13.36	13.60	11.70	13.60	15.70	4.24	4.89	4.43	6.45	6.06
421	13.29	12.60	9.70	12.80	14.92	4.63	4.04	3.65	5.54	5.41
442	13.16	12.38	9.64	13.16	14.66	3.98	3.78	3.19	5.08	4.98
475	11.73	12.32	11.53	12.45	13.76	5.21	4.11	5.26	4.70	4.76
489	11.30	11.86	10.13	11.69	11.03	4.67	3.90	3.12	4.54	4.67
516	10.31	11.15	9.27	11.28	13.68	4.21	4.02	3.11	4.34	4.34
523	11.90	11.86	9.92	12.12	13.62	4.93	4.21	3.24	4.54	4.80
550	10.05	11.61	9.98	12.32	13.42	5.33	4.54	3.44	4.93	5.06
579	10.44	11.61	9.47	11.80	13.10	4.93	4.28	3.31	4.54	4.67
600	11.09	11.41	10.37	11.80	13.19	6.03	4.54	3.24	4.73	4.73
628	11.07	10.96	10.24	12.32	13.49	6.74	4.73	3.50	4.86	4.86
649	11.73	10.50	10.83	12.20	12.70	6.63	4.67	3.63	4.15	4.60
670	11.12	9.79	10.18	11.73	13.06	7.26	4.67	3.56	3.89	4.47
691	11.73	9.85	10.76	12.58	14.10	6.29	4.40	3.63	4.28	4.86
715	13.36	10.63	12.25	15.36	13.26	5.77	4.60	3.92	4.77	4.93
733	12.77	10.30	10.96	15.50	14.10	5.90	5.35	4.96	8.30	5.22
747	12.77	10.95	11.67	14.97	13.00	6.94	5.19	4.28	7.00	5.41
754	12.30	10.14	10.24	12.80	14.10	6.00	5.00	4.54	7.75	5.30
765	12.40	10.80	10.70	13.60	15.40	6.90	5.00	4.15	5.96	5.87
786	12.40	10.00	10.60	14.50	14.98	6.60	4.80	4.10	5.00	5.50
814	12.58	11.86	11.44	13.68	12.50	6.74	5.80	4.38	5.58	5.77
832	11.50	10.90	9.60	13.20	13.10	7.40	5.90	4.30	9.70	6.20
849	11.30	11.00	9.20	12.10	11.99	7.30	6.20	4.40	6.00	6.30
875	10.24	10.44	8.69	10.57	11.73	6.68	5.77	4.44	5.28	5.84
891	10.37	9.66	7.78	9.66	10.76	6.60	5.77	4.40	5.28	6.03
913	8.43	8.43	7.10	8.60	10.10	6.48	5.96	4.20	5.38	5.80
932	7.53	7.66	6.46	8.63	10.13	6.26	5.80	4.33	5.40	6.46
954	7.83	7.53	6.86	9.00	10.13	6.13	5.60	4.00	5.70	5.56
975	8.18	6.92	7.05	8.48	9.14	5.92	5.52	3.86	5.25	5.65

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
999	7.53	6.53	7.36	8.49	9.26	5.86	6.73	4.26	5.66	5.76
1016	5.53	6.20	6.92	8.53	8.66	5.46	6.03	4.33	5.23	5.4
1048	5.53	7.00	7.46	9.13	9.20	4.43	6.1	4.46	6	5.93
1069	5.78	6.25	6.15	7.90	8.80	4.5	5.8	4.45	5.79	5.59
1084	5.92	6.12	5.99	7.45	8.65	4.3	5.52	4.2	5.65	5.72
1090	5.20	5.99	6.12	7.25	9.58	4.2	5.75	4.35	5.65	5.79
1111	5.70	5.85	5.65	7.11	9.24	4.4	5.72	4.32	5.52	5.58

APPENDIX VII

Leachate pH

	Recycle Columns					Single Pass Columns				
Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	COL 2	COL 3	COL 4	COL 5	COL 8
53	3.87	4.29	3.99	4.08	3.94	4.26	3.98	3.92	3.90	4.04
58	4.68	4.58	4.67	4.71	4.55	5.04	4.47	4.41	4.48	5.03
67	4.72	4.53	4.55	4.91	4.60	4.96	4.48	4.41	4.48	4.96
88	6.11	4.54	4.51	4.91	4.95	5.17	4.68	4.47	4.40	4.95
105	5.46	4.53	4.56	4.85	4.56		4.72	4.49	4.51	4.84
127	5.43	4.54	4.57	4.87	4.63	5.04	4.90	4.50	4.53	4.69
139	5.18	4.59	4.63	5.28	4.68	5.06	6.05	4.33	4.67	4.56
163	5.11	4.66	4.52	5.65	5.04	5.07	5.71	4.70	5.16	4.90
178	4.98	4.71	4.62	5.73	5.02	5.20	5.69	5.44	5.86	4.63
197	5.06	5.93	4.77	5.57	5.98	5.05	5.55	5.65	5.93	4.83
222	4.87	5.45	4.71	5.30	5.75	4.78	5.60	5.18	5.51	5.18
245	4.99	5.57	6.09	5.39	5.83		5.27	5.22	5.44	5.37
284	4.95	5.33	5.62	5.20	5.61	4.85	5.13	5.10	5.12	5.15
287	4.95	5.35	5.62	5.26	5.60	4.86	5.17	5.15	5.24	5.20
307	4.93	5.28	5.37	5.23	5.41	4.80	5.08	5.05	5.14	5.14
313	4.88	5.24	5.31	5.32		4.78	5.10	5.11	5.12	5.05
330	5.03	5.33	5.31	5.31	5.53	4.91	5.10	5.14	5.13	5.03
342	4.98	5.34	5.43	5.35	5.56	4.87	5.13	5.14	5.13	5.09
356	5.02	5.37	5.37	5.37	5.52	4.92	5.17	5.15	5.17	5.07
370	5.02	5.36	5.36	5.39	5.52	4.99	5.19	5.11	5.16	5.02
385	5.02	5.33	5.35	5.34	5.49	4.93	5.15	5.08	5.16	5.01
398	5.07	5.36	5.41	5.42	5.51	4.90	5.24	5.17	5.25	5.08
421	4.95	5.29	5.29	5.34	5.40	4.93	5.17	5.10	5.17	4.97
442	4.96	5.34	5.38	5.41	5.48	4.92	5.20	5.16	5.25	5.06
475	5.05	5.34	5.40	5.38	5.47	5.07	5.29	5.22	5.28	5.14
489	5.03	5.24	5.24	5.15	5.35	4.98	5.21	5.14	5.21	5.01
512	4.95	5.18	5.21	5.24	5.30	4.97	5.14	5.11	5.17	5.02
523	5.16	5.36	5.40	5.42	5.51	5.18	5.39	5.35	5.30	5.22
550	5.20	5.30	5.35	5.40	5.40	5.10	5.25	5.30	5.30	5.20
579	5.00	5.20	5.25	5.30	5.30	5.00	5.20	5.20	5.20	5.05
600	5.00	5.20	5.30	5.30	5.30	5.30	5.30	5.20	5.30	5.10
628	5.10	5.20	5.30	5.30	5.30	5.00	5.30	5.20	5.30	5.10
649	5.15	5.30	5.50	5.40	5.40	5.10	5.40	5.30	5.40	5.20
670	5.10	5.20	5.35	5.30	5.20	5.10	5.20	5.10	5.20	5.10
691	5.05	5.20	5.50	5.45	5.40	5.00	5.20	5.10	5.20	5.20
715	5.20	5.40	5.75	5.60	5.45	5.10	5.40	5.30	5.40	5.30
733	5.20	5.30	5.58	5.50	5.40	5.17	5.45	5.38	5.90	5.28
747	5.15	5.30	5.55	5.50	5.40	5.12	5.31	5.25	5.60	5.25
754	5.15	5.30	5.52	5.40	5.35	5.12	5.31	5.22	5.64	5.30
765	5.15	5.30	5.50	5.45	5.40	5.12	5.30	5.25	5.50	5.30
786	5.20	5.30	5.50	5.50	5.55	5.10	5.30	5.20	5.35	5.30
814	5.30	5.50	5.65	5.60	5.60	5.30	5.50	5.40	5.50	5.50
832	5.25	5.40	5.55	5.50	5.50	5.30	5.50	5.40	5.50	5.40
849	5.30	5.60	5.70	5.70	5.70	5.40	5.50	5.50	5.60	5.60
875	5.25	5.60	5.80	5.80	5.75	5.40	5.50	5.45	5.60	5.50
891	5.30	5.60	5.70	5.80	5.75	5.30	5.50	5.45	5.60	5.50

[illegible]

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
913	5.30	5.50	5.70	6.00	5.80	5.30	5.50	5.45	5.60	5.50
932	5.30	5.55	5.60	5.85	5.90	5.32	5.50	5.45	5.80	5.50
954	5.40	5.50	5.50	5.70	5.85	5.30	5.45	5.40	5.50	5.40
975	5.50	5.40	5.40	5.65	5.80	5.20	5.40	5.30	5.40	5.35
999	6.90	5.65	5.55	5.70	5.95	5.60	5.70	5.50	5.50	5.50
1016	7.20	5.70	5.60	5.60	5.95	5.40	5.45	5.45	5.48	5.40
1048	7.15	5.70	5.85	5.60	5.90	6.00	5.58	5.60	5.65	5.55
1069	7.15	5.70	6.60	6.10	5.80	6.35	5.45	5.40	5.35	5.50
1084	7.10	5.70	6.70	6.20	5.80	6.70	5.20	5.20	5.20	5.30
1090	6.95	5.70	6.85	6.50	5.80	6.70	5.30	5.30	5.30	5.30
1111	7.10	6.00	6.80	6.50	5.80	6.55	5.30	5.20	5.20	5.25
1130	7.10	6.18	7.05	6.10	5.85	6.70	5.40	5.30	5.30	5.30

APPENDIX VIII

Leachate Iron Concentration (mg/L)

Days Since Loading	Recycle Columns					Single Pass Columns				
	COL 1	COL 6	COL 7	COL 9	COL 10	COL 2	COL 3	COL 4	COL 5	COL 8
49	715.0	540.0	630.0	900.0	620.0	260.0	710.0	540.0	570.0	780.0
59	575.0	595.0	730.0	1090.0	705.0	290.0	805.0	935.0	650.0	855.0
67	950.0	770.0	800.0	850.0	790.0	320.0	950.0	1100.0	780.0	1040.0
88	850.0	840.0	1030.0	880.0	730.0	450.0	1100.0	1230.0	1030.0	830.0
99	870.0	1040.0	800.0	790.0	875.0	390.0	1090.0	1260.0	1020.0	940.0
106	890.0	1080.0	850.0	860.0	870.0	430.0	850.0	1155.0	1240.0	960.0
125	870.0	1170.0	790.0	930.0	855.0	405.0	1175.0	1135.0	1120.0	1155.0
148	830.0	1426.0	1087.0	1002.0	1155.0	440.0	1040.0	1900.0	1290.0	1630.0
162	917.0	1358.0	1087.0	1155.0	1053.0	577.0	1222.0	1630.0	1188.0	1630.0
169	813.0	1110.0	964.0	957.0	849.0	691.0	942.0	1110.0	1040.0	1626.0
179	590.0	1180.0	719.0	957.0	734.0	791.0	1020.0	1090.0	1090.0	1550.0
189	734.0	1100.0	777.0	971.0	874.0	446.0	856.0	806.0	942.0	
197	730.0	976.0	1106.0	988.0	988.0	471.0	941.0	871.0	1042.0	1000.0
212	753.0	947.0	1153.0	918.0	976.0			802.0	1007.0	906.0
225	659.0	960.0		994.0	1024.0			741.0	929.0	723.0
239	349.0	573.0	645.0	466.0	591.0		327.0	224.0	367.0	358.0
262	426.0	556.0	717.0	573.0	1080.0		412.0	367.0	430.0	349.0
282	493.0	672.0	806.0	717.0	806.0	392.0	305.0	273.0	493.0	471.0
295	493.0	627.0	717.0	896.0	739.0	448.0	448.0	493.0	627.0	448.0
316	635.0	816.0	756.0	967.0	1180.0	453.0	363.0	393.0	695.0	665.0
330			1090.0	998.0	1030.0	514.0	423.0	574.0	650.0	726.0
351	763.0	947.0	789.0	1263.0	1263.0	276.0	174.0	229.0	750.0	268.0
391	789.0	789.0	947.0	1260.0	1340.0	211.0	138.0	150.0	710.0	316.0
407	868.0	868.0	947.0	1263.0	1263.0	146.0	142.0	189.0	631.0	205.0
430	1440.0	1290.0	1420.0	1860.0	1860.0	217.0	217.0	248.0	929.0	341.0
448	1390.0	1140.0	1030.0			268.0	248.0	237.0	237.0	330.0
473	1190.0	825.0	1340.0	1390.0	1240.0	299.0	242.0	217.0	340.0	289.0
518	888.0	740.0	740.0	888.0	1040.0	281.0	222.0	236.0	592.0	214.0
538	888.0	666.0	814.0	1040.0	740.0	252.0	192.0		310.0	281.0
560	1040.0	888.0	888.0	1040.0	1180.0	267.0	222.0	258.0	532.0	592.0
603	165.0					94.0	94.0	94.0		
623		684.0	999.0	1160.0	1260.0		273.0	736.0	894.0	868.0
732	870.0					695.0	428.0			
753	1131.0	481.0	695.0	950.0	909.0	749.0	321.0	695.0	588.0	722.0
772	990.0	468.0	602.0	883.0	775.0	588.0	321.0	251.0	347.0	508.0
795	990.0	401.0	347.0	668.0	695.0	588.0	347.0	384.0	548.0	535.0
816	1150.0	428.0				642.0	401.0	481.0	561.0	
837	722.0	401.0	321.0	722.0	588.0	243.0	428.0	615.0	535.0	481.0
858	144.0	428.0	374.0	562.0	749.0	695.0	525.0	508.0	535.0	508.0
879	830.0	307.0	294.0	401.0	749.0	615.0	428.0	535.0	695.0	642.0
900	508.0	165.0	193.0	294.0	454.0	668.0	749.0	521.0	668.0	535.0
921	219.0	125.0	120.0	173.0	168.0	776.0	588.0	588.0	588.0	883.0
942	194.0	109.0	136.0	321.0	401.0	642.0	481.0	668.0	749.0	690.0
963	187.0	187.0	144.0	281.0	535.0	254.0	508.0	270.0	428.0	722.0
984	183.0	155.0	624.0	396.0	457.0	188.0	488.0	670.0	777.0	548.0
1005	177.0	198.0	210.0	219.0	225.0	344.0	283.0	265.0	307.0	579.0

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
1026	171.0	210.0	235.0	244.0	213.0	186.0	113.0	238.0	298.0	341.0
1047	146.0	179.0	199.0	229.0	183.0	400.0	104.0	222.0	280.0	246.0
1173	6.8	400.0	63.8	123.8	837.5	96.2	1525.0	1125.0	3137.5	4275.0
1194	26.0	300.0	136.2	400.0	700.0	243.8	3168.8	2025.0	1787.5	1875.0
1222	30.0	96.2	56.9	387.5	1337.5	587.5	1500.0	1400.0	2675.0	2675.0

[illegible]

Leachate Zinc Concentration (mg/L)

	Recycle Columns					Single Pass Columns				
Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	COL 2	COL 3	COL 4	COL 5	COL 8
49	105.0	77.8	714.0	689.0	918.0	38.3	153.0	344.0	498.0	1630.0
59	135.0	93.0	346.0	122.0	550.0	20.5	91.6	194.0	299.0	900.0
67	153.0	179.0	523.0	485.0	829.0	45.9	191.0	485.0	523.0	1810.0
88	53.6	204.0	434.0	319.0	753.0	51.0	98.2	536.0	510.0	1680.0
99	56.1	217.0	395.0	293.0	810.0	44.6	95.7	504.0	536.0	1580.0
106	63.8	191.0	421.0	319.0	765.0	51.7	153.0	491.0	446.0	1735.0
125	37.5	200.0	140.0	200.0	570.0	71.5	62.5	585.0	702.0	1060.0
148	69.0	141.0	280.0	240.0	215.0	36.0	48.0	365.0	537.0	1110.0
162	72.0	159.0	315.0	240.0	850.0	70.0	60.0	425.0	572.0	1120.0
169	56.0	88.0	262.0	188.0	900.0	60.0	45.0	450.0	450.0	600.0
179	60.0	90.0	112.0	150.0	600.0	41.0	45.0	450.0	338.0	938.0
189	45.0	90.0	112.0	112.0	675.0	38.0	38.0	100.0	300.0	
197	46.0	60.0	233.0	173.0	692.0	33.0	33.0	153.0	233.0	773.0
212	53.0	46.0	240.0	180.0	612.0			140.0	193.0	588.0
225	40.0	53.0		193.0	508.0			120.0	220.0	493.0
239	46.3	55.0	212.0	190.0	750.0		38.1	68.8	310.0	463.0
262	42.5	46.3	166.0	233.0	812.0		98.8	30.0	295.0	437.0
282	41.3	38.9	153.0	227.0	800.0	28.2	24.0	83.1	219.0	409.0
295	38.1	32.5	114.0	245.0	753.0	32.5	21.9	71.3	260.0	325.0
316	2.5	12.5	35.0	112.0	900.0	1.3	21.0	12.5	130.0	170.0
330			45.0	170.0	975.0	14.5	24.5	17.5	116.0	160.0
351	43.0	42.0	52.5	140.0	788.0	33.0	20.0	25.0	115.0	183.0
391	44.0	33.5	57.5	165.0	825.0	30.5	17.5	38.0	82.5	167.0
407	39.0	44.0	55.0	140.0	825.0	21.0	18.5	42.0	95.0	140.0
430	30.5	37.0	30.6	144.0	632.0	15.5	14.2	29.2	71.2	113.0
448	27.0	38.5	8.7			13.0	10.5	25.6	85.0	77.5
473	15.0	15.0	61.3	160.0	231.0	11.9	14.1	24.3	52.5	90.0
494	28.7	25.0	33.7	25.0	562.0	15.0	13.2	22.5	43.7	46.2
518	19.0	27.5	62.5	225.0	300.0	12.8	18.8	18.8	75.0	100.0
538	18.8	12.6	48.1	225.0	300.0	23.8	8.8	12.5	62.5	100.0
560	22.5	26.2	53.8	262.0	300.0	11.2	11.2	15.0	75.0	138.0
581	18.8	27.5	53.8	225.0	300.0	6.8	6.2	12.5	62.5	138.0
603	16.0					10.0	8.0	11.0		
623	25.0	31.0	62.0	125.0	312.0	12.0	5.0	12.0	75.0	112.0
732	17.5					0.0	4.0			
753	18.0	15.5	47.8	67.8	102.5	2.0	0.7	16.0	55.0	46.8
772	18.0	17.2	41.1	57.5	118.0	5.5	5.5	13.5	20.0	42.2
795	17.0	12.0	31.0	120.0	91.2	5.5	5.5	16.0	46.5	42.2
816	21.0	14.7	35.0	47.5	90.0		5.2	17.5	14.0	48.0
837	9.5	12.5	29.0	55.0	60.0	5.5	6.5	15.0	53.8	43.0
858	4.2	13.0	19.5	34.2	48.8	3.0	7.0	18.0	43.5	46.8
879	18.2	22.2		68.2	85.1	0.0	13.6	34.1	78.9	76.1
900	6.8	27.3	22.7	56.8	68.1	4.5	4.5	20.4	79.4	76.1
921	2.3	5.7	11.4	27.3	42.0		9.1	52.3	34.0	22.7
942		10.2	18.2	34.1	34.1		6.8	11.4	45.4	34.1
963				31.6	43.2					46.0

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
984	0.0	2.9	5.6	50.3	49.7	0.0	1.8	3.0	3.8	48.6
1005	0.0	1.9	9.9	45.2	62.3	0.0	1.0	0.0	2.4	59.4
1026	0.0	0.0	10.4	45.2	46.8	0.0	0.0	0.0	0.0	43.4
1047	0.0	0.0	8.8	38.8	38.3	0.0	0.0	0.0	0.0	40.0
1068	0.3	2.0	6.5	53.5	46.0	1.3	11.5	21.5	32.5	52.5
1089	0.2	3.5	1.5	41.5	47.5	0.5	12.5	18.5	33.5	30.0
1110	0.3	2.5	1.5	20.0	28.5	1.2	11.0	15.0	32.0	30.0
1131	0.1	4.0	1.3	16.1	24.3	0.0	17.5	15.9	40.0	25.9
1173	0.0	5.5	2.5	15.5	57.0	2.5	8.8	17.5	41.2	59.0
1194	2.5	2.5	2.5	17.0	50.5	2.5	11.8	17.6	105.0	105.0
1222	2.5	3.5	3.0	22.2	42.5	0.0	10.2	16.2	41.2	50.8

Leachate Nickel Concentration (mg/L)

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
49	2.2	1.7	74.0	68.0	158.0	0.2	1.6	46.0	62.0	181.0
59	1.5	1.2	28.4	47.5	57.5	0.8	1.2	26.4	33.6	80.5
67	2.8	2.9	39.0	43.5	143.0	0.4	3.1	39.0	67.0	46.0
88	2.6	2.8	24.0	43.0	139.0	0.5	2.9	37.0	60.0	58.5
99	2.8	3.5	2.8	44.0	148.0	0.3	2.5	36.8	62.0	21.8
106	1.6	2.8	2.8	48.5	145.0	1.3	2.6	33.5	55.5	204.0
125	2.8	3.5	39.6	55.0	125.0	1.4	3.0	42.0	97.4	221.0
148	1.2	4.2	49.0	61.2	183.0	0.4	2.9	54.8	108.5	229.0
162	3.3	5.9	50.4	75.2	180.0	1.3	2.3	68.6	114.0	198.0
169	2.6	2.1	46.6	69.9	197.0	3.6	2.0	65.7	88.1	200.0
179	2.1	4.1	31.4	69.7	162.0	3.6	2.6	77.7	77.7	197.0
189	2.1	3.4	36.3	67.3	206.0	0.8	1.6	44.0	98.5	
197	1.9	2.0	39.8	54.7	203.4	1.0	1.8	31.2	62.9	134.8
212	1.8	2.2	4.5	66.8	213.6			35.6	63.3	139.9
225	1.5	2.4		84.6	216.1			28.0	77.6	159.0
239	1.0	1.4	42.3	73.4	133.0		0.8	11.1	80.1	109.0
262	2.0	2.2	44.5	89.0	156.0		2.0		82.3	102.0
282	1.6	2.6	53.0	103.0	270.0	1.1	1.0	25.6	77.5	103.0
295	2.1	2.4	55.5	129.0	271.0	0.5	0.5	23.2	77.5	116.0
316	1.0	1.2	11.0	33.0	140.0	0.4	0.4	8.5	31.3	42.5
330		0.4	14.5	40.3	200.0	0.4	0.4	3.0	26.6	37.5
351	0.7	5.8	1.4	38.0	100.7	0.4	0.4	12.0	29.4	14.5
391	0.8	1.0	18.8	45.8	175.0	0.0	0.0	1.3	21.5	36.3
407	1.8	1.1	17.5	43.1	168.5	0.8	0.0	1.3	18.8	31.0
430	1.8	2.5	38.4	78.3	307.0	0.0	0.3	17.5	15.4	46.1
448	0.6	2.5	30.7			0.3	0.3	9.9	19.2	43.0
473	1.2	2.1	36.9	69.1	230.0	6.3	0.3	16.0	20.0	36.9
494	1.2	2.1	26.1	24.6	214.0	1.2	0.3	14.1	18.4	24.6
538	0.0	0.0	20.0	46.0	50.0	1.5	0.0	3.0	14.0	23.0
560	0.0	1.5	16.8	44.2	152.4	0.0	0.0	3.8	13.0	21.3
581	0.0	0.0	15.2	39.6	121.9	0.0	0.0	4.6	12.2	19.8
603	0.0					0.0	0.0	1.5		
623		0.7	23.0	49.2	200.9		0.0	5.0	15.8	23.4
732	1.0					0.4	0.8			
753	0.7	0.8	8.4	21.6	35.3	0.0	0.6	2.6	13.2	11.1
772	0.8	0.7	11.9	29.5	73.8	0.3	0.2	7.0	11.6	12.7
795	0.6	0.8	10.6	29.0	32.7	0.5	0.4	6.5	10.4	12.1
816	0.4	1.0	11.2	34.8	44.3		0.4	9.2	11.5	13.4
858		3.6	53.9	82.9	50.3	1.0		41.5	38.5	65.2
879	0.0	0.0	0.0	20.0	21.8	0.0	0.0	5.4	9.1	12.3
900	0.0	0.0	4.1	9.8	19.5	1.8	3.2	4.2	7.3	12.1
921	8.0	0.0	16.2	9.3	8.0	0.0	0.0	6.3	9.3	12.6
942	0.0	0.0	4.6	6.9	6.9	0.0	0.9	9.0	0.0	13.0
963	0.0	2.3	9.3	20.1	26.4	0.0	0.0	9.3	18.1	13.2
984	0.0	0.0	7.4	22.6	19.6	0.0	1.8	7.3	8.0	26.5
1005	0.0	0.0	6.3	26.5	30.4	0.0	0.0	6.6	8.1	8.4

[illegible]

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
1026	0.0	0.0	4.0	24.5	28.5	0.0	0.0	2.4	6.0	7.7
1047	0.0	0.0	5.7	20.6	26.5	0.0	0.0	1.8	6.0	15.2
1068	0.4	0.4	3.3	15.6	26.0	0.2	0.4	7.3	20.8	27.0
1089	0.0	1.0	10.4	9.3	23.9	0.0	0.6	4.2	7.3	27.0
1110	0.4	0.2	5.2	11.1	23.5	0.0	0.4	6.9	2.0	30.0
1173	0.2	0.6	1.0	4.2	14.0	0.4	0.6	5.2	14.2	20.0
1194	0.7	0.7	1.0	5.6	3.1	0.2	0.8	6.9	9.2	18.0
1222	1.3	0.6	1.4	5.0	30.2	0.4	0.6	5.5	17.0	28.8

Leachate Lead Concentration (mg/L)

	Recycle Columns					Single Pass Columns				
s Since ding	COL 1	COL 6	COL 7	COL 9	COL 10	COL 2	COL 3	COL 4	COL 5	COL 8
49	4.5	1.1	9.6	9.6	3.9	0.0	2.5	3.4	2.8	35.1
59	4.9	3.3	7.5	4.5	7.5	0.2	31.0	8.4	3.5	26.3
67	4.5	5.6	10.6	3.9	3.4	0.0	4.5	14.0	5.1	27.0
88	0.1	7.9	9.0	0.6	10.6	0.2	5.1	16.9	5.6	11.8
99	0.6	7.9	7.9	1.1	11.0	0.1	3.4	15.7	5.1	22.5
106	0.1	7.9	7.9	2.8	12.9	0.1	3.9	16.6	6.2	21.3
125	1.0	7.0	7.0	4.5	11.5	0.8	3.7	13.0	7.5	17.5
148	0.0	5.0	6.9	0.7	12.6	0.5	1.0	12.0	5.8	15.1
162	0.5	5.1	9.5	1.0	8.8	0.5	1.0	10.5	5.1	15.9
169	0.0	7.0	7.8	1.0	14.8	0.0	0.0	13.3	4.0	3.0
179	0.0	8.0	7.5	0.5	11.0	0.0	0.0	5.0	1.2	17.5
189	0.0	2.5	5.0	0.5	8.0	0.0	0.0	0.5	0.5	
197	0.0	0.1	5.4	0.2	3.8	0.0	0.0	0.0	0.2	5.4
212	0.0	0.1	5.0	0.0	1.7			0.0	0.0	3.8
225	0.0	0.1		0.0	1.2			0.0	0.0	1.7
239	0.0	0.0	1.0	0.0	0.7		0.0	0.0	0.0	0.7
262	0.0	0.0	0.5	0.0	1.0		0.5	0.0	0.0	2.7
282	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	3.2
295	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	2.9
316	0.0	0.0	0.0	0.4	2.7	0.0	0.0	0.0	0.0	6.3
330		0.0	0.0	0.0	2.7	0.0	0.0	0.0	0.0	11.2
351	0.3	0.0	0.0	0.8	1.5	0.0	0.0	0.0	0.0	10.0
391	0.0	0.0	0.0	0.8	3.9	0.0	0.0	0.0	0.0	10.1
407	0.0	0.0	0.0	1.2	5.6	0.0	0.0	0.0	0.0	10.0
430	0.0	0.0	0.0	0.6	2.0	0.0	0.0	0.0	0.0	2.6
448	0.0	0.0	0.0			0.0	0.0	0.0	0.0	2.1
473	0.0	0.0	0.0	0.3	3.2	0.0	0.0	0.0	0.0	2.3
494	0.0	0.0	0.0	0.3	3.6	0.0	0.0	0.0	0.0	2.0
518	0.0	0.0	0.0	1.0	18.0	0.0	0.0	0.0	0.0	2.0
538	0.0	0.0	0.0	2.0	10.0	0.0	0.0	0.0	0.0	4.0
560	0.0	0.0	3.0	9.0	20.0	0.0	0.0	0.3	7.0	10.0
581	0.0	0.3	0.3	0.9	6.6	0.2	0.2	0.9	0.9	1.6
603	0.2					0.0	0.0	0.3	0.0	
623	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.7
732	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
753	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
772	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
795	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
816	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
837	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
858	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
879	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
900	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
921	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
942	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
963	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

[illegible]

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
984	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1005	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1026	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1047	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Leachate Cadmium Concentration (mg/L)

s Since ding	COL 1	COL 6	COL 7	COL 9	COL 10	COL 2	COL 3	COL 4	COL 5	COL 8
	Recycle Columns					Single Pass Columns				
49	0.1	0.1	34.1	33.4	35.8	0.0	0.8	10.4	17.1	85.9
59	0.3	0.2	19.2	29.9	34.2	0.0	0.4	8.0	13.8	76.2
67	0.1	0.1	23.9	22.7	35.8	0.0	0.2	40.6	15.5	80.0
88	0.0	0.1	18.5	20.0	32.2	0.0	0.1	11.6	14.0	76.4
99	0.2	0.1	16.7	18.5	36.4	0.0	0.3	11.3	13.7	75.2
106	0.1	0.2	17.3	18.2	37.0	0.0	0.1	11.2	13.7	74.0
125	0.1	0.1	21.7	10.3	31.0	0.0	0.2	9.8	15.5	35.6
148	0.1	0.2	11.4	8.4	41.2	0.1	0.1	14.6	13.7	45.6
162	0.1	0.1	10.4	8.4	43.6	0.1	0.1	18.5	27.2	44.9
169	0.1	0.1	13.6	10.8	56.6	0.5	0.1	30.5	25.9	29.8
179	0.1	0.2	11.7	13.0	51.7	1.0	0.1	27.3	18.4	55.9
189	0.1	0.1	11.4	10.6	69.5	0.1	0.1	17.9	18.9	
197	0.1	0.1	9.9	9.8	49.9	0.1	0.1	12.5	14.0	49.9
212	0.1	0.1	9.9	11.9	48.5			12.0	12.4	48.0
225	0.1	0.1		11.5	54.6			11.4	14.1	55.3
239	0.1	0.0	6.8	12.3	41.9		0.0	5.8	11.8	49.8
262	0.1	0.0	3.7	15.5	49.8		0.0		10.5	49.8
282	0.0	0.0	5.0	18.2	63.5	0.0	0.0	6.1	27.3	61.0
295	0.0	0.0	5.1	24.3	67.0	0.0	0.0	4.8	27.3	59.0
316	0.0	0.0	1.3	11.3	62.5	0.0	0.0	1.0	12.1	50.0
330			1.6	12.1	71.3	0.0	2.3	6.3	11.1	65.0
351	0.0	1.3	0.0	10.5	57.0	0.0	0.0	2.2	10.8	55.0
391	0.0	0.0	2.0	23.0	65.0	0.0	0.0	1.7	1.5	50.0
407	0.0	0.0	1.8	25.0	66.3	0.0	0.0	0.5	8.0	27.5
430	0.0	0.0	1.1	21.2	60.0	0.0	0.0	0.5	20.0	37.5
448	0.0	0.0	2.4			0.0	0.0	1.2	3.7	11.5
473	0.0	0.0	5.0	7.0	22.2	0.0	0.0	1.2	4.5	9.5
494	0.0	0.0	2.3	3.0	15.3	0.1	0.0	1.0	4.5	6.0
560	0.0	3.2	1.4	8.5	40.0	0.0	0.0	0.2	0.2	7.8
581	0.0	0.0	1.8	10.5	4.5	0.0	0.0	0.0	3.5	8.5
603	0.0	0.0				0.0	0.0	0.2		
623	0.0	0.0	3.2	14.2	37.5	0.0	0.0	0.0	6.8	12.2
732	0.1					0.0	0.0			
753	0.0	0.0	1.5	6.8	22.5	0.0	0.0	0.9	4.5	4.6
772	0.0	0.0	1.3	7.0	21.5	0.0	0.0	0.7	1.2	5.2
795	0.0	0.0	1.0	12.5	21.5	0.0	0.0	0.2	3.9	5.8
879	0.0	0.0	0.0	4.3	5.4	0.0	0.0	1.7	4.6	4.7
900	0.0	4.7	2.2	3.9	5.2	0.4	0.0	1.7	1.7	5.2
921	0.0	0.0	0.6	3.0	4.7	0.0	0.0	1.5	4.3	5.2
942	0.0	0.0	0.4	3.0	4.9	0.0	0.0	1.7	5.4	4.9
963	0.0	0.0	0.9	4.1		0.2	0.0	1.7	4.9	3.2
984	0.0	0.0	0.3	1.0	0.5	0.0	0.0	0.2	0.4	0.0
1005	0.0	0.0	0.4	0.8	0.5	0.0	0.0	0.2	0.2	0.0
1026	0.0	0.0	1.1	2.0	1.7	0.0	0.0	0.2	1.0	0.3
1047	0.0	0.0	0.3	2.0	1.9	0.0	0.0	0.5	2.2	1.5
1068	0.0	0.0	0.0	1.4	1.7	0.0	0.0	0.7	3.8	3.3

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
1089	0.0	0.0	0.0	1.1	1.4	0.0	0.0	0.8	1.4	4.0
1110	0.0	0.0	0.0	5.0	2.0	0.0	0.0	0.4	3.8	4.3
1173	0.5	0.5	0.5	0.4	1.6	0.5	0.5	0.8	3.6	4.6
1194	0.5	0.5	0.5	0.3	1.8	0.5	0.5	0.7	2.9	4.0
1222	0.5	0.5	0.5	0.4	2.4	0.5	0.5	0.6	3.6	4.2

Leachate Mercury Concentration (ug/L)

Days Since Loading	Recycle Columns					Single Pass Columns				
	COL 1	COL 6	COL 7	COL 9	COL 10	COL 2	COL 3	COL 4	COL 5	COL 8
49	1.0	1.0	1266.0	281.0	41.0	1.0	1.0	164.0	45.0	4094.0
59	1.0	46.0	1.0	2700.0	75.0	1.0	1.0	1.0	42.0	387.0
67	1.0	1.0	217.0	50.0	22.0	1.0	1.0	11.5	22.0	2593.0
88	1.0	1.0	133.0	96.0	28.0	1.0	1.0	20.0	15.0	1550.0
99	1.0	1.0	239.0	66.0	43.0	1.0	1.0	9.0	17.0	1453.0
106	1.0	1.0	84.0	83.0	23.0	1.0	1.0	13.0	13.0	855.0
125	1.0	1.0	48.0	43.0	31.0	1.0	1.0	6.0	8.0	151.0
147	1.0	1.0	104.0	12.0	28.0	1.0	1.0	30.0	28.0	123.0
163	1.0	1.0	96.0	31.0	45.0	1.0	1.0	123.0	26.0	162.0
170	1.0	1.0	80.0	18.0	36.0	1.0	1.0	221.0	30.0	133.0
180	1.0	1.0	54.0	37.0	65.0	1.0	1.0	109.0	14.0	209.0
190	1.0	1.0	20.0	13.0	28.0	1.0	1.0	18.0	49.0	1.0
197	1.0	1.0	29.0	36.0	66.0	1.0	1.0	50.0	55.5	125.0
212	1.0	1.0	23.0	9.5	37.0	0.0	0.0	14.5	16.0	56.0
228	1.0	2.0	29.0	18.0	39.0	0.0	0.0	26.5	16.0	123.0
239	1.0	1.0	25.0	14.0	33.0	0.0	1.0	12.0	16.0	61.0
262	2.0	2.0	18.9	5.6	21.8		2.0	7.5		
282	2.7	2.3	12.2	13.7	18.3	4.0	1.5	6.5	7.4	38.9
295	2.5	2.1	12.2	6.3	14.5	0.0		9.6	4.3	15.3
316	2.5	0.0	27.8	68.3	68.3	0.0	0.0	22.9	6.1	85.6
330		6.5	24.2	18.3	28.0	7.6	1.7	16.7	6.6	76.8
351	3.6	1.8	12.8	10.9	11.4	3.6	1.8	4.5	3.6	27.4
391	2.4	1.2	10.1	14.7	16.6	1.2	2.4	3.7	3.3	44.9
407	0.8	1.2	18.6	15.1	17.4	0.4	4.9	16.2	2.9	27.6
430	2.3	0.0	18.6	33.1	17.1	6.8	10.8	61.7	11.4	51.4
448	0.0	0.0	6.6	9.9	8.8	4.4	3.8	9.8	3.6	41.7
473	0.0	2.0	13.0	6.0	18.0	1.7	3.0	12.0		
496	1.0	2.0	21.0	14.0	13.0	0.0	0.0	18.0	10.0	36.0
518	0.0	0.0			30.0	6.0	0.0	14.0	4.0	29.5
538	0.0	2.1	23.8	19.2	24.4	3.6	3.6	16.8	12.0	64.9
560	0.0	1.8	27.1	16.6	31.4	0.9	3.5	14.3	9.6	65.4
581	5.8	8.7	2.9	20.9	18.0	6.2	5.4	3.6	18.0	18.8
602	1.4	1.4	24.5	11.5	29.6	4.3	5.0	15.9	10.1	23.1
623	0.0	0.0	25.4	18.8		0.0	0.0	7.7	6.6	56.8
644	0.0	0.0	8.8	7.7	12.1	0.0	0.0	12.1	12.1	41.9
665	0.0	0.0	0.0	0.0	9.4	0.0	0.9	0.0	0.4	19.7
686	0.0	0.0	2.3	8.1	14.6	0.0	0.0	0.0	12.8	9.8
732	6.5	0.0	7.6	9.7	6.5		9.7	13.0	10.8	11.9
753	4.3	6.5	5.4	9.7	6.5	4.3	6.5	7.6	9.7	10.7
816	4.1	1.6	8.1	4.9	17.9		4.9	13.0	13.8	17.1
837	0.0	0.0	9.8	6.5	16.6	0.0	5.7	9.0	9.0	14.7
879	0.0	0.0		11.4	26.1	1.6	4.1	7.3	4.5	16.3
900	0.0	0.0	6.4	4.8	7.2	0.0	2.7	8.7	3.7	7.3
921	0.0	0.0	16.5	9.2	10.1	0.0	3.6	5.5	3.7	6.4
938	0.0	0.0	6.4	6.4	9.6	0.0	0.8	4.8	0.0	4.0
963	0.0	0.0	21.6	10.8	0.0	0.0	0.0	12.3	0.0	0.0

[illegible]

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
984	0.0	12.3	17.0	15.4	18.5	0.0	0.0	9.2	10.8	15.4
1005	0.0	0.0	11.9	6.5	11.9	0.0	12.3	18.5	18.5	11.9
1026	0.0	0.0	8.9	11.9	8.9	0.0	0.0	11.9	4.4	0.0
1047	0.0	0.0	10.4	11.9	11.9	0.0	0.0	8.9	11.9	13.4

Leachate Chromium Concentration (mg/L)

Days Since Loading	Recycle Columns COL 1	COL 6	COL 7	COL 9	COL 10	Single Pass Columns COL 2	COL 3	COL 4	COL 5	COL 8
49	18.5	0.1	7.4	17.0	5.5	0.1	0.8	10.6	2.6	39.0
59	0.5	0.8	6.0	2.3	4.0	0.6	1.0	9.3	2.5	11.4
67	8.5	0.5	10.2	6.0	4.4	0.0	0.7	6.6	4.1	32.0
88	2.1	0.5	8.4	22.0	4.9	0.1	0.8	4.5	7.3	26.5
99	1.2	0.5	9.7	2.0	5.8	0.0	0.5	4.4	8.0	24.5
106	1.1	0.5	8.4	2.0	5.5	0.6	0.8	4.6	8.0	25.0
125	1.0	1.2	4.8	2.1	5.9	0.5	1.0	9.0	9.3	11.4
148	0.0	0.2	3.4	0.0	4.7	0.1	0.0	3.4	0.8	12.0
162	1.5	0.0	1.4	0.3	3.7	0.1	0.1	3.9	0.0	7.1
169	1.2	0.0	2.7	0.9	2.3	0.5	0.1	3.1	1.3	8.8
179	0.0	0.9	1.6	0.1	5.4	1.5	0.3	2.2	1.5	9.1
189	0.8	0.9	1.7	0.9	3.8	0.7	0.5	0.4	1.2	
197	0.5	0.1	2.0	0.2	4.3	0.2	0.1	0.3	0.6	2.7
212	0.6	0.0	1.8	0.2	2.5			0.3	0.2	2.0
225	0.4	0.0		0.2	2.0			0.2	0.2	1.2
239	0.1	0.0	0.5	0.1	2.0		0.0	0.1	0.1	0.4
262	0.5	0.0	0.3	0.0	2.5		0.0	0.0	0.0	0.2
282	0.1	0.0	0.2	0.0	1.4	0.0	0.0	0.0	0.1	0.2
295	0.0	0.0	0.1	0.0	1.1	0.0	0.0	0.0	0.0	0.2
316	0.0	0.0	0.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0
330		0.0	0.1	0.1	2.8	0.0	0.0	0.0	0.0	0.3
351	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0
391	0.0	0.0	0.0	0.0	22.0	0.0	0.0	0.0	0.0	0.0
407	0.0	0.0	0.0	0.0	23.0	0.0	0.0	0.0	0.0	0.0
430	1.3	1.3	1.9	1.3	5.9	0.0	1.3	0.0	0.0	0.0
448	2.0	0.0	2.3			0.0	0.0	1.8	0.3	2.0
473	0.0	0.0	1.3	0.0	8.7	0.0	0.0	0.0	0.0	0.8
494	0.0	2.0	0.0	3.4	2.7	1.8	0.0	0.0	1.3	1.3
538	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
560	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
581	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
603	0.0	0.0	0.0			0.0	0.0		0.0	
623	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
732	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
753	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
772	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
795	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
816	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
837	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
858	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
879	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.8	0.3
900	0.0	0.0	0.7	0.0	0.1	0.0	0.0	0.0	0.8	0.3
921	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
942	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
963	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
984	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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	Recycle Columns					Single Pass Columns				
Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10	COL 2	COL 3	COL 4	COL 5	COL 8
1005	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1026	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1047	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1173	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1194	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX IX

Student t Test on Cumulative Gas Production

Fundamental equations (Ott, 1977):

Sample variance, $S_i^2 = (\ x^2 - (\ x)^2/\ n)/(n - 1)$

Test statistic, $t = \dfrac{\bar{x}_1 - \bar{x}_2}{[(S_1^2/n_1) + (S_2^2/n_2)]^{\frac{1}{2}}}$

Example: Delta 2-3/Delta 2-8

$$t = \frac{3838.4 - 3666.3}{[(163{,}247.8/10) + (129{,}682.8/10)]^{\frac{1}{2}}}$$

$t = 1.0$ which is less than $t_{0.975,df=9}$ which is 2.262

Therefore, at the 95% confidence level, there is no significant difference, with respect to Column 2 (CS), between the total gas production of columns 3 (OS) and 8 (OHS).

Summary of tests performed using attached data:

Test	Calculated t	t, 95% confidence level
Delta 2-3/Delta 2-8	1.0	2.262
Delta 2-5/Delta 2-3	9.4	"
Delta 2-4/Delta 2-5	6.1	"
Delta 1-7/Delta 1-9	1.3	"
Delta 1-10/Delta 1-7	5.4	"
Delta 1-8/Delta 1-2	3.6	"
Delta 1-5/Delta 1-8	1.7	"
Delta 1-4/Delta 1-5	1.0	"
Delta 1-4/Delta 1-8	2.8	"

Cumulative Gas Production
(L at standard temperature and pressure)

Days Since Loading	COL 2	COL 3	COL 4	COL 5	COL 8
1041	7744	4617	1676	2902	4706
1051	8014	4705	1768	2974	4826
1061	8269	4780	1841	3029	4916
1071	8531	4854	1916	3080	5011
1081	8750	4906	1970	3121	5079
1091	8895	4931	1994	3142	5111
1101	9102	4983	2034	3179	5187
1111	9251	5012	2053	3199	5220
1121	9297	5020	2066	3204	5226
1131	9375	5036	2071	3213	5283

Days Since Loading	Delta 2-3	Delta 2-4	Delta 2-5	Delta 2-8
1041	3127	6068	4842	3038
1051	3309	6246	5040	3188
1061	3489	6428	5240	3353
1071	3677	6615	5451	3520
1081	3844	6780	5629	3671
1091	3964	6901	5753	3784
1101	4119	7068	5923	3915
1111	4239	7198	6052	4031
1121	4277	7231	6093	4071
1131	4339	7304	6162	4092
Mean	3838.4	6783.9	5618.5	3666.3
Variance	163247.8	169336.2	192831.8	129682.8
n	10	10	10	10

Cumulative Gas Production
(L at standard temperature and pressure)

Days Since Loading	COL 1	COL 6	COL 7	COL 9	COL 10
1041	40882	33798	19440	20329	16226
1051	42349	35110	20142	20934	16641
1061	43669	36331	20773	21527	17002
1071	44953	37508	21383	22136	17366
1081	46024	38507	21898	22718	17712
1091	46752	39184	22185	23068	17951
1101	47600	39956	22545	23434	18254
1111	48323	40620	22801	23726	18498
1121	48641	40910	22877	23825	18581
1131	49013	41241	22953	23975	18711

Days Since Loading	Delta 1-6	Delta 1-7	Delta 1-9	Delta 1-10
1041	7084	21442	20553	24656
1051	7239	22207	21415	25708
1061	7338	22896	22142	26667
1071	7445	23570	22817	27587
1081	7517	24126	23306	28312
1091	7568	24567	23684	28801
1101	7644	25055	24166	29346
1111	7703	25522	24597	29825
1121	7731	25764	24816	30060
1131	7772	26060	25038	30302
Mean	7504	24121	23253	28126
Variance	46448	2213793	2055033	3364738
n	10	10	10	10

Cumulative Gas Production
(L at standard temperature and pressure)

Days Since Loading	COL 1	COL 2	COL 3	COL 4	COL 5	COL 8
1041	40882	7744	4617	1676	2902	4706
1051	42349	8014	4705	1768	2974	4826
1061	43669	8269	4780	1841	3029	4916
1071	44953	8531	4854	1916	3080	5011
1081	46024	8750	4906	1970	3121	5079
1091	46752	8895	4931	1994	3142	5111
1101	47600	9102	4983	2034	3179	5187
1111	48323	9251	5012	2053	3199	5220
1121	48641	9297	5020	2066	3204	5226
1131	49013	9375	5036	2071	3213	5283

Days Since Loading	Delta 1-2	Delta 1-3	Delta 1-4	Delta 1-5	Delta 1-8
1041	33138	36265	39206	37980	36176
1051	34335	37644	40581	39375	37523
1061	35400	38889	41828	40640	38753
1071	36422	40099	43037	41873	39942
1081	37274	41118	44054	42903	40945
1091	37857	41821	44758	43610	41641
1101	38498	42617	45566	44421	42413
1111	39072	43311	46270	45124	43103
1121	39344	43621	46575	45437	43415
1131	39638	43977	46942	45800	43730
Mean	37098	40936	43882	42716	40764
Variance	4461580	6328592	6364573	6506699	6109060
n	10	10	10	10	10

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APPENDIX X

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